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ORIGINAL ARTICLE

ReD shoes: actuated footwear for multisensory redirected walking in virtual reality

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Abstract

A major challenge in virtual reality (VR) is enabling users to navigate expansive virtual environments within confined real-world spaces. Although redirected walking (RDW) addresses this by manipulating users' walking paths, it is hindered by visual-vestibular inconsistencies, leading to reduced immersion, discomfort, and constrained detection thresholds (DTs). We introduce ReD Shoes, redirecting shoes for VR locomotion with dynamically adjustable inclination designed to enhance multisensory integration by providing haptic feedback directly to the feet. This feedback mitigates visual-vestibular inconsistencies by enhancing proprioceptive cues and aligning tactile sensations with visual stimuli, thereby improving self-motion perception, presence, and gait stability. We conducted two experiments with 30 participants: 10 in a pilot study to optimize inclination parameters and 20 in a main study to evaluate the DT, gait stability, and user experience under No Inclination, Low Inclination (1 cm), and High Inclination (1.5 cm) conditions. Low Inclination considerably expanded the DT (43.64%), enhanced the user's feel of presence, and maintained walking stability through effective multisensory alignment. In comparison, High Inclination showed a smaller DT expansion (33.86%), increased discomfort, reduced stability, and aggravated oculomotor symptoms due to intensified sensory conflicts. This study demonstrates the use of ReD Shoes in addressing key RDW limitations by enhancing DT, stability, and user presence through active haptic feedback. Our findings offer insights for developing advanced VR mobility solutions, supporting adaptive haptic footwear that improves RDW functionality and extends immersive VR applications in gaming, training, and rehabilitation.

Keywords Virtual reality · Redirected walking · Detection thresholds · Haptic device · Gait stability

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1 Introduction

The growing use of virtual reality (VR) technologies in various fields—ranging from entertainment and gaming to education and professional training (Elsharkawy et al. 2024a, b)—has heightened the need for effective techniques that facilitate naturalistic movement within virtual environments (VEs) (Nilsson et al. 2018). A major challenge in creating immersive VR experiences is allowing users to navigate extensive virtual spaces while being confined to the physical limitations of smaller real-world areas (Nilsson et al. 2018). Redirected walking (RDW) addresses this challenge by altering a user's physical walking path, to enable continuous movement through larger virtual spaces (Razzaque 2005).

RDW works by visually manipulating the VR environment in response to user movements, allowing users to traverse a virtual space smoothly while staying within the confines of a smaller physical area and avoiding collisions (Steinicke et al. 2010). For example, if a user walks straight in a VE, RDW can subtly curve their real-life path into an arc by rotating the virtual world around them. However, as the degree of visual manipulation increases, RDW can reach a threshold where visual–vestibular inconsistencies become perceptible. This inconsistency occurs when altered visual input conflicts with the user's proprioceptive and vestibular senses, potentially leading to a heightened awareness of the manipulation, reduced sense of presence, and increased risk of simulation sickness (Akiduki et al. 2003; Caserman et al. 2021). Consequently, RDW techniques are limited by a detection threshold (DT), beyond which users become aware of the manipulations. This constrains the extent to which virtual space can be expanded effectively (Kruse et al. 2018; Bölling et al. 2019).

To enhance the effectiveness of RDW and extend the DT, while RDW studies have primarily relied on visual stimuli—such as applying visual cues within the VR scene to prevent users from noticing manipulation (Lee et al. 2024a, b; Matsumoto et al. 2016a, b)—recent research has explored incorporating additional sensory modalities, such as haptic feedback. Haptic feedback improves the sense of presence (Elsharkawy et al. 2024a, b) and reduces user awareness of manipulation (Matsumoto et al. 2019; Matsumoto et al. 2016a, b). Visuo-haptic techniques, like the "Unlimited Corridor" and "Handrail," use passive haptic cues alongside visual stimuli to simulate unrestricted movement within confined spaces, expanding RDW's applicability across various domains. However, these methods often require large physical infrastructures, which limits their flexibility and scalability.

Wearable devices offer a more adaptable approach to enhancing RDW without extensive physical setups. For example, devices that induce the hanger reflex by applying pressure to specific body points, such as the knee or hand, create illusory force perceptions that affect the DT in VR (Fukui et al. 2023; Tanaka et al. 2023). These findings suggest that wearable devices may enhance RDW techniques, however they also present challenges, as their effectiveness can vary depending on individual walking or movement styles.

Among the various approaches, foot-based passive haptic feedback systems for improving immersion and VR presence have gained increasing interest (Nagao et al. 2018; Kasarda et al. 2020; Matsumoto et al. 2017). The foot, which is directly involved in the act of walking, is an intuitive choice for delivering haptic feedback that is aligned with natural gait mechanics (Frey 2007). Humans often cannot detect light slopes and perceive themselves as walking on level ground when the incline is minimal (Hu et al. 2019; Yamaguchi et al. 2019). This characteristic makes the foot a promising target for enhancing RDW by aligning tactile cues with visual stimuli, such as tilting mechanisms in footwear, which can create the illusion of directional changes or elevation shifts without disrupting balance or orientation.

Research has shown that tactile feedback through the feet, such as skin stretch and mechanoreception, plays a crucial role in proprioception—the body's sense of position and movement (Kurosaki and Nakata 2022). The superficial mechanical vibrations applied to the sole of the foot can enhance the central nervous system's ability to maintain equilibrium by providing kinematic information about the body position (Edin and Johansson 1995). The plantar sole acts as a dynamometric map, where sensory input from the skin helps regulate muscle contractions and movement (Kavounoudias et al. 1998). These findings suggest that foot-based haptic feedback can reduce sensory conflicts and increase DT in VR environments by better aligning tactile and visual cues.

Our study builds on these insights by introducing "ReD Shoes," a novel actuated approach to foot-based haptic feedback in VR inspired by the classic 1948 film the ReD Shoes (Sullivan and Stein 2000). In the film the protagonist's red shoes lead her into a world of endless, enchanting movement, creating a deeply immersive experience. Similarly, our "ReD Shoes" are designed to redirect the users' movement path seamlessly and enhance their sense of presence in Ves, Fig. 1. These shoes use tilting mechanisms to align tactile feedback with vestibular and visual cues, thereby enhancing the user's walking experience in VR without disrupting balance or orientation. By harmonizing these sensory inputs, "ReD Shoes" aim to enhance RDW experience, reducing perceptual discrepancies between physical and virtual movements.

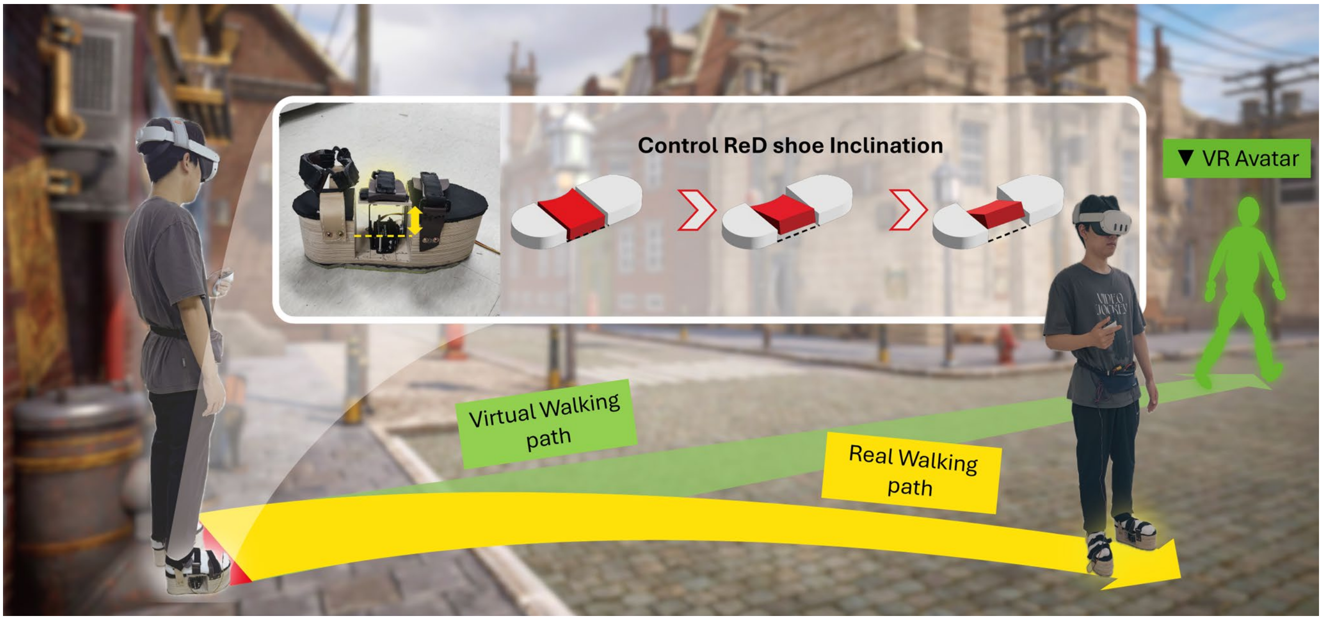


Fig. 1 Conceptual illustration of the ReD Shoes in action, demonstrating the control of shoe inclination to enable redirected walking in a virtual environment

To explore the potential of the ReD shoes, we conducted two experiments to determine the optimal design parameters to maximize user comfort and effectiveness in RDW. The first experiment, a pilot study, identified the best inclination levels and configurations to minimize discomfort while enhancing walking tendencies in VR. The results also determined whether applying the slope mechanism to one or both feet was more effective. The second experiment focused on evaluating the DT of RDW under different inclination conditions and its influence on user experience, including presence, perceived workload, motion sickness, and gait stability.

Our research addresses the following questions:

RQ1 How do different degrees of the ReD Shoes' inclination impact the DT for RDW?

RQ2 How do the tactile sensations generated by the ReD Shoes influence users' sense of presence, perceived workload, and motion sickness during RDW?

RQ3 How do different tilting inclinations in the ReD Shoes affect the walking behavior and gait stability of VR users during RDW?

Through these investigations, we aim to understand how inclination integration influences the DT and evaluate the ReD Shoes' potential to enhance RDW in real-world VR applications.

2 Related work

2.1 RDW and DT

Walking is a fundamental mode of interaction in VR, offering a natural and immersive way for users to engage with VEs (Nilsson et al. 2018; Peng et al. 2020). However, immersion is often constrained by the physical limitations of real-world spaces, which may include obstacles such as furniture and walls. These barriers restrict movement and pose safety risks for users navigating the virtual world while wearing head-mounted displays (HMDs).

RDW is an innovative technique proposed by Razzaque et al. to bridge the gap between limited physical space and expansive VE navigation (Razzaque 2005). RDW manipulates the user's perception of movement and direction, thereby allowing continuous exploration within a confined physical area (Nilsson et al. 2018; Razzaque 2005). This is achieved by applying redirection gains—rotation, translation, and curvature gains—that subtly alter the user's physical movements without their awareness, and enhance their sense of presence in the virtual environment.

The rotation gain manipulates the degree of physical turns to differ from those in the virtual space (Lee et al. 2024a, b; Lee et al. 2025), while the translation gain alters the perceived distance, which makes the virtual journey feel longer or shorter than the actual physical movement (Nilsson et al. 2018; Kruse et al. 2018). Curvature gain, bends the user's straight pathway into a curved trajectory, which allows for undetectable navigation around physical obstructions undetectably, thus maintaining a continuous virtual experience. The proposed method not only prevents collisions but also expands the usable space within VR by making users' movements more efficient and natural (Razzaque 2005).

Our study focused on curvature gain, which has been recognized for its effectiveness in expanding spatial experiences in RDW environments (Bölling et al. 2019). This technique facilitates smooth directional changes and allows continuous movement without frequent reset interventions and enhances user engagement (Lee et al. 2024a, b).

Although RDW effectively addresses the constraints of physical space in VR, it may introduce visual–vestibular inconsistencies, particularly when a user navigates around an obstacle or within a confined space. Such inconsistencies may increase the risk of motion sickness or reduce the user's sense of presence if the user becomes aware of the manipulation (Steinicke et al. 2010). The DT is a critical component of RDW, as it represents the minimum intensity of manipulation that users can perceive; a manipulation intensity that exceeds this threshold renders the manipulation detectable and negatively impacts the user experience.

Steinicke et al. introduced a novel way to measure DTs using a two-alternative forced-choice (2AFC) approach (Akiduki et al. 2003). Participants were asked questions like "Was the virtual movement smaller or greater than the physical movement?" and "Is the physical path bent left or right?" while they experienced variations in rotation, translation, and curvature gains as they were walking (Akiduki et al. 2003). The subjects' responses were limited to choosing between "smaller/greater" or "left/right" options, respectively. The gain value was then defined as the point of subjective equality (PSE), which was the point at which physical and virtual movements were perceived to be equal based on average participant responses. The upper DT (UDT) and lower DT (LDT) were identified around the PSE, which were the perceptual points at which participants could detect discrepancies between physical and virtual movements with 75% accuracy. In our study, DTs were measured by randomly applying seven curvature gains ($\pm\pi/90, \pm\pi/45, \pm\pi/30$, and 0) to participants, where each level of curvature gain was repeated six times to ensure reliable data.

2.2 Visuo-haptic feedback for RDW

Passive haptic feedback, which relies on external physical elements to provide tactile sensations, has been extensively studied as a method to enhance VR experiences, particularly for RDW. In the context of RDW, passive haptic feedback is designed to align tactile sensations with visual stimuli, thereby increasing the sense of presence and immersion.

Many RDW studies have relied primarily on visual stimuli, such as visual cues in VR scenes, to prevent users from detecting manipulations of their physical walking path. For example, previous studies have used optical flow or virtual avatars to guide users without their awareness (Lee et al. 2024a, b; Nguyen et al. 2020). However, recent research has demonstrated that incorporating an additional sensory modality, such as haptic feedback, may further enhance the effectiveness of RDW by extending the DT.

Researchers have explored various redirection techniques that use visuo-haptic interactions to enhance RDW with the intent to improve user immersion and extend the DT (Matsumoto et al. 2019; Matsumoto et al. 2016a, b; Kohli et al. 2005; Hwang et al. 2023a, b). This research began with the idea of reusing a single passive haptic prop in RDW to deliver tactile feedback (Kohli et al. 2005). For example, Matsumoto et al. introduced the "Unlimited Corridor" technique, which allows users to perceive an infinitely long corridor within a VE by physically interacting with a curved wall (Matsumoto et al. 2019; Matsumoto et al. 2016a, b) or a handrail (Matsumoto et al. 2016a, b). This approach creates the illusion of a continuous corridor or handrail when users touch the haptic prop while walking. Their findings indicate that haptic cues, such as touching a physical object, can make manipulations of the curvature in a VE less noticeable to users. However, these studies relied on haptic props fixed to specific locations in real environments, which limited their application to room-scale VR in dynamic or varied environments. To address this limitation, other studies have proposed the use of dynamic haptic devices such as robot-based systems with two movable robots and a doorknob to simulate door-opening redirection (Hoshikawa et al. 2024). Although these methods aimed to enhance immersion with timely haptic feedback, they had shortcomings due to their reliance on extended infrastructure, which could lead to potential delays, collisions, higher costs, and limited flexibility and scalability in different VR environments.

Wearable devices have gained traction in RDW research as a means to provide more natural and immersive VR experiences. Unlike passive haptic feedback, which relies on fixed external elements, wearable devices interact directly with the user's body to offer a mobile and adaptable solution for RDW in various environments. These devices include wearable sensors that deliver vibrotactile feedback according to the user's position within VE (Fukui et al. 2023; Kurosaki and Nakata 2022; Tanaka et al. 2023). The goal of these wearable devices is to simulate continuous walking sensation without requiring expansive physical spaces or stationary installations. Wearable devices represent an alternative way to enhance presence in dynamic and varied VR settings.

Studies have explored the use of the hanger reflex, which is an illusory perception of force created by applying pressure to specific points on the body, in different RDW contexts. For example, a knee-type reflex device was found to influence user walking paths although it did not considerably affect the DT of RDW (Fukui et al. 2023). In contrast, applying a reflex device to the hand increased the DT for hand redirection in VR (Tanaka et al. 2023). These findings suggest that wearable devices may enhance RDW techniques, however they also present challenges, as their effectiveness can vary depending on individual walking or movement styles (Fukui et al. 2023; Tanaka et al. 2023). For example, the knee-type hanger reflex guides walking by controlling toe position, but participants whose gait relies more on inner or outer thigh movement are less likely to be affected.

Therefore, our "ReD shoes" approach aims to overcome these limitations by providing dynamic, foot-based haptic feedback that does not rely on large, fixed installations, enabling more flexible and scalable RDW solutions in diverse VR environments.

2.3 Foot-based haptic feedback in VR

Haptic stimulation of the foot has been extensively studied in VR research, particularly for vertical redirection, due to its intuitive and direct effect on walking (Nagao et al. 2018, 2017; Kasarda et al. 2020). The feet are continuously in contact with the ground, which makes them a natural interface for conveying spatial information, such as the sensation of elevation or descent. Such spatial information can enhance the realism and immersion of VR experiences (Frey 2007). Research has demonstrated that tactile information transmitted through the feet can be easily perceived and understood intuitively; thus, it is ideal for guiding users in VR environments (Frey 2007; Hu et al. 2019).

Several foot-targeted haptic systems have been designed to simulate vertical redirection in VR using passive materials. For example, previous studies have proposed installing physical materials on the ground in a real-life environment to provide haptic feedback to users while they ascend and descend stairs in VR, which can improve their sense of presence and accuracy of height perception (Nagao et al. 2018). These studies also demonstrated that elongated props offer a better user experience than more conventional haptic props, or they further enhance immersion and realism (Kasarda et al. 2020). Overall, the findings indicate that haptic feedback provided solely to the feet enhanced the user's sense of presence and increased the accuracy of height prediction while the user was ascending or descending stairs.

To address the limitations of haptic feedback methods, which often require a fixed physical setup or substantial infrastructure, researchers have developed alternative solutions that do not rely on static physical environments (Otaran and Farkhatdinov 2021; Schmidt et al. 2015; Ohashi et al. 2023). For example, Otaran et al. introduced a haptic feedback ankle platform that facilitates virtual interactive walking control by using ankle motion while the user is seated (Otaran and Farkhatdinov 2021). Similarly, the "Motorized Level Ups" system simulates virtual terrain at different elevations using a pair of mechanically brake-actuated shoes, and it offers the advantage of functioning over a large, potentially infinite area (Schmidt et al. 2015).

Other research has focused on measuring the DT range while participants traverse both actual and visually manipulated step heights (3, 5, and 7 cm). The findings indicated that the virtual step heights were generally perceived as approximately 1 cm lower than the actual step heights, regardless of the variation, and that the DT range decreased as the actual step height increased (Kobayashi et al. 2019). Additional studies have continued to investigate similar systems and explore other dimensions of haptic feedback related to vertical redirection, such as the evaluation of different device forms and the optimization of user experience through various prop designs (Hu et al. 2019; Matsumoto et al. 2017; Ishikawa et al. 2018).

Foot-based haptic systems have also been used with inclination or roll-tilting to induce vertical redirection in VR. Research findings have suggested that in the presence of a slight inclination, humans tend to shift their posture and walking trajectory toward the lower side of a slope. This supports the feasibility of using controlled inclinations for RDW (Frey 2007; Yamamoto et al. 2018; Casali and Wierwille 1980; Nie and Rosenberg 2021; Zhang and Hong 2021). For example, studies have measured changes in the walking direction when two shoes are at different heights, and they have found that the walking direction tends to bend toward the side of the shoe at a lower height (Jung et al. 2018; Zhang and Hong 2021). Additionally, a shoe-type device has been proposed to help visually impaired individuals navigate by exploiting their natural tendency to adjust to slight slopes (Frey 2007). This phenomenon, which mirrors visually induced tilting effects, demonstrates a promising basis for shoe-based inclination systems in RDW applications.

Despite the promising results obtained using foot-based haptic feedback for vertical redirection, challenges remain. For example, although a difference in shoe height of up to 2 cm does not greatly influence walking, larger differences may increase motion sickness, which indicates a need for careful calibration of these systems (Jung et al. 2018; Zhang and Hong 2021). Moreover, studies that measured the perception of slope inclination have found that visual cues can distort a user's sense of verticality, which may lead to less accurate assessments of incline and reduce the effectiveness of VR systems in some VR scenarios (Maeda et al. 2016). However, previous studies have also demonstrated that subtle roll-angle manipulations, such as tilting up to $\pm 1.93°$, are often imperceptible to users (Maeda et al. 2016), suggesting that this approach is viable for redirection without inducing discomfort.

Although most foot-targeted haptic systems have focused on vertical redirection, there remains a significant opportunity to extend these principles to horizontal reorientation, potentially providing a more comprehensive solution for enhancing immersion and realism in VR environments. However, these systems have not been developed for RDW, limiting their effectiveness and versatility in guiding user movement across dynamic virtual spaces.

2.4 Gait stability

Gait stability refers to an individual's ability to walk without losing balance or falling, particularly when encountering disturbances during movement (Bruijn et al. 2013). Previous studies have demonstrated that VR and RDW can negatively influence gait stability, which poses a risk for users wearing HMDs who cannot fully perceive their physical surroundings (Hollman et al. 2007; Janeh et al. 2017; Mohler et al. 2007). Additionally, walking on inclined surfaces—whether upward or downward—has been found to further reduce gait stability as the angle of inclination increases. Various methods have been employed to assess human balance in these contexts. For example, a study have measured center of mass (CoM) displacement using a Vive Tracker positioned at the lumbar region in a VR-based system (Liang et al. 2021), while others have used insole sensors to track plantar pressure (Hwang et al. 2023a, b), or have utilized a Microsoft Kinect camera to track foot position and orientation for gait training in VEs (Paolini et al. 2014).

However, the design of our "ReD Shoes," which includes inclined surfaces, makes the use of insole sensors or Vive trackers impractical because these devices can cause discomfort to users. To overcome this, we employed an Intel RealSense D435 depth camera (Intel RealSense 2024) to capture three-dimensional data on participants' posture and movement. Using the MediaPipe machine learning framework (MediaPipe 2024), we extracted joint positions and calculated the (CoM) to evaluate gait stability. Additionally, we measured cadence, defined as the number of steps per minute (Mohammadzada et al. 2022), to provide a comprehensive assessment of the "ReD Shoes'" impact on user stability. Recent studies have demonstrated that MediaPipe Pose achieves high accuracy in gait analysis during normal walking, confirming its suitability for extracting stability-related parameters in controlled environments (Hii et al. 2023).

3 Pilot study: defining the design and operational criteria for the red shoes

A pilot study was conducted to determine whether inclinations should be applied to one foot or to both feet and to identify the range of inclination that minimizes discomfort and maximizes the change in the walking trajectory. The pilot study utilized regular shoes with various inclination configurations to guide the design of the ReD shoes and identify the operational inclination range that could be tested with the ReD shoes.

3.1 Setup

The experiment was conducted in a 9 × 9 m lab room and involved 10 participants (6 males, 4 females; aged (M = 23.4, SD = 2.5)). The participants were asked to wear custom-designed shoes equipped with outsoles made of strong foam board shaped into slopes of varying heights. The outsoles were modular, which allowed for their easy attachment or removal from the shoe body using micro Velcro tape.

During the experiment, participants walked approximately 7 m in a straight line toward a wall while wearing an Oculus Quest 2 HMD that simulated a typical VR walking scenario but did not employ RDW techniques. The participants' trajectory is shown in Fig. 2b. As previous studies had shown that limb length differences greater than 2 cm could cause significant gait asymmetry, we created models of the inclination slope to have four different heights: 0.5, 1, 1.5, and 2 cm (Zhang and Hong 2021). These inclinations were assessed under two configurations: a single-sided inclination, "S", (applied only to the left side of the shoes) and a double-sided inclination, "D", (applied to both sides), as shown in Fig. 2a. The order of all the experimental conditions were randomized. In total, each participant walked 7 m under 10 different configurations, and each configuration was tested twice. Therefore, each participant completed the 7 m walk 20 times.

3.2 Measurements

We measured the participants' walking trajectory using position data from the head-tracking system of the VR HMD, using methods similar to those used in (Bölling et al. 2019), which employed the coordinates of the participant's head position to analyze the tendencies of the walking trajectory. This method avoided attaching hardware to the feet, preserving comfort during the pilot phase. As demonstrated by

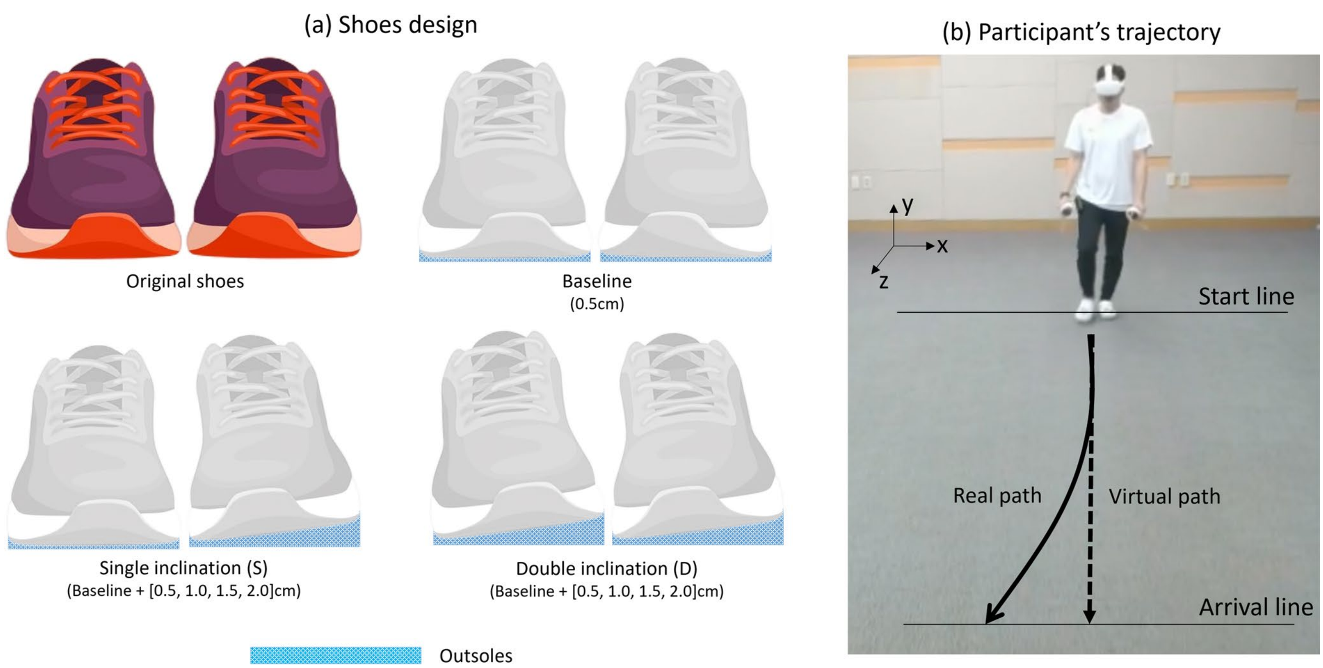


Fig. 2 Illustration of pilot study setup. **a** Variations in shoe design for different inclination configurations; **b** participant's walking trajectory, showing real and virtual paths

Boulo et al. (2023), the Oculus Quest 2 achieves positional accuracy within ~ 1 cm under static conditions and exhibits limited drift of 0.64–5.83 cm during short-distance walking, validating the suitability of the headset for brief locomotion studies. Given the short walking distance and duration in our pilot study, our goal was not precise locomotion profiling but identifying inclination ranges that minimized discomfort and altered walking trajectories. As potential drift would equally affect all conditions, headset-based tracking was sufficient to capture these relative effects. Additionally, we collected data on subject discomfort using a questionnaire. The questionnaire assessed the participants' perception of discomfort while walking (Q: "My shoes were uncomfortable while walking."). The participant responses were recorded on a 5-point Likert scale whose values ranged from "strongly disagree" (1) to "strongly agree" (5). The 5-point Likert scale was not used to define the comfort level of each inclination or to select the best inclination value. Instead, it was employed to identify the inclination range for which the discomfort values were rated as low, and the identified inclination range was tested with the ReD shoes in the main experiment.

3.3 Pilot study results

3.3.1 Walking trajectory analysis

An analysis of the difference in the x-direction between the initial and arrival positions, as presented in Fig. 2b, showed that participants had a clear tendency to drift in the direction of the inclination, as shown in Table 1. This effect was more pronounced when the inclinations were applied bilaterally, which suggests that double-sided inclinations have a greater impact on walking trajectory.

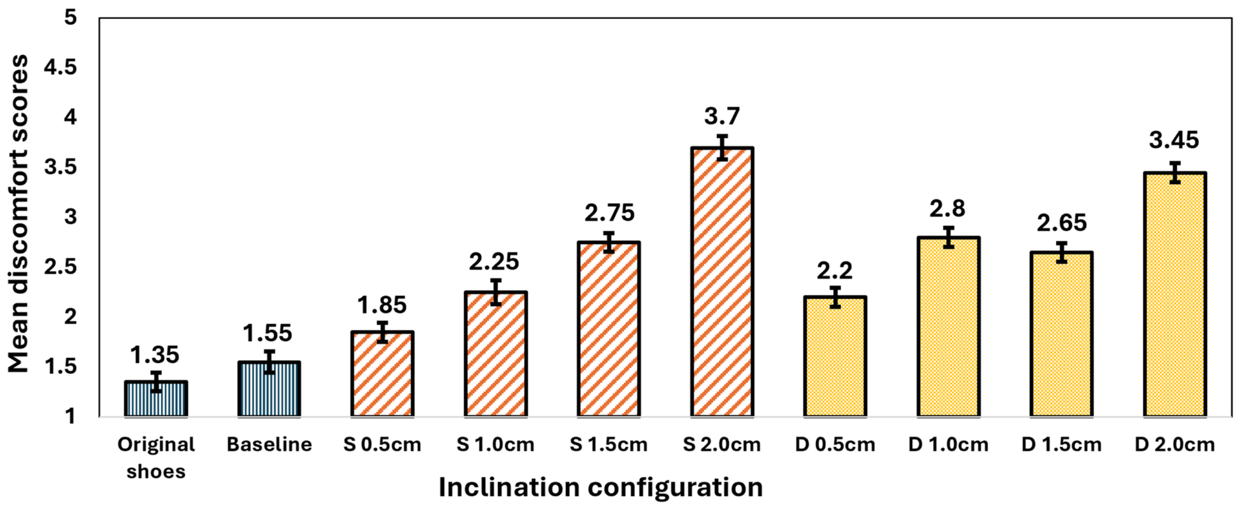
Table 1 X-direction average position differences in walking trajectories for single-sided (S) and double-sided (D) inclinations

Inclination configurations	Difference in x-direction position (m)	Inclination configurations	Difference in x-direction position (m)
Original shoes	0.103	Baseline	0.09
S 0.5 cm	0.179	D 0.5 cm	0.147
S 1.0 cm	0.141	**D 1.0 cm**	**0.259**
S 1.5 cm	0.093	**D 1.5 cm**	**0.221**
S 2.0 cm	0.233	D 2.0 cm	0.415

3.3.2 Walking discomfort

The results shown in Fig. 3 indicate that the discomfort scores increased with greater levels of inclination. The double-sided inclinations generally resulted in higher discomfort scores than did the single-sided inclinations, with the highest discomfort reported for a 2.0 cm inclination for both configurations.

We further conducted a nonparametric Friedman test to evaluate the differences in discomfort level across ten inclination configurations. The results indicated that inclination had a significant effect on discomfort ($\chi^2(9) = 64.621$, $p < 0.001$, Kendall's $W = 0.718$), thereby highlighting notable



Significance Test

Inclination pair		Asterisk	Inclination pair		Asterisk
Original shoes	S1.0 cm	**	Baseline	D2.0 cm	**
Original shoes	S1.5 cm	**	S0.5 cm	S1.5 cm	**
Original shoes	S2.0 cm	**	S0.5 cm	S2.0 cm	**
Original shoes	D0.5 cm	**	S0.5 cm	D1.0 cm	**
Original shoes	D1.0 cm	**	S0.5 cm	D1.5 cm	**
Original shoes	D1.5 cm	**	S0.5 cm	D2.0 cm	**
Original shoes	D2.0 cm	**	S1.0 cm	S2.0 cm	**
Baseline	S1.0 cm	*	S1.0 cm	D2.0 cm	**
Baseline	S1.5 cm	**	S2.0 cm	D0.5 cm	**
Baseline	S2.0 cm	**	D0.5 cm	D1.0 cm	*
Baseline	D1.0 cm	**	D0.5 cm	D2.0 cm	**
Baseline	D1.5 cm	**			

Fig. 3 Average discomfort scores and pairwise significance across for participants walking with ten different inclination configurations: “S” for single-sided inclination and “D” for double-sided inclination (* $p<0.05$; ** $p<0.01$)

differences in perceived discomfort across configurations, as shown in Fig. 3. A post-hoc analysis using Conover’s test further revealed significant differences between several configurations. However, no significant differences in discomfort were observed between S 1.0 cm and either of D 1.0 cm or D 1.5 cm, nor between S 1.5 cm and either of D 1.0 cm or D 1.5 cm.

3.3.3 Design implications

Our pilot study findings indicate that the double-sided inclinations have a more pronounced effect on walking trajectory than the single-sided inclinations, which aligns with the results of previous research (Aruin and Kanekar 2013). The greatest impact was observed for the steepest double-sided inclination of 2.0 cm, followed by inclinations of 1.5 and 1.0 cm. Additionally, there was a clear trend of increasing discomfort scores with the higher inclinations; discomfort was greatest for the double-sided inclination of 2.0 cm but lower for 1.5 and 1.0 cm. These results suggest that double-sided inclinations of 1.0 or 1.5 cm could work as compromised inclinations to provide a notable effect on walking trajectory while minimizing discomfort.

4 Red shoes implementation

4.1 Shoe design

The ReD Shoes were designed as a modular system consisting of separate sections that could be assembled manually (e.g., the top, middle, and bottom sections), as shown in Fig. 4. The connection between the sections was designed as a rigid structure using a precise peg-in-hole insertion technique, thereby creating a high-friction fit that ensures stability and prevents any unwanted movement between the parts. The primary material used for constructing the ReD Shoes was wood, which was chosen for its rigidity and durability. The wooden design allowed for the firm attachment of the straps and foam to enhance fit and comfort for the user. Each shoe weighed 0.9 kg, a weight achieved by using the wooden frame, which reduced the overall weight and made the shoes suitable for prolonged use in VR applications.

Figure 4a shows the stationary parts of the top part of the ReD Shoes. Figure 4b shows the moving part of the top portion, which is directly connected to the actuation mechanism. This mechanism allows rotation with one-degree-of-freedom (1-DOF) and allows controlled movement to the right and left.

In Fig. 4c, the middle connecting structure is shown as a compromising two stationary parts at the front and back of the shoe. These parts were designed to ensure sufficient strength and load-bearing capacity to safely support the user's weight (Cen et al. 2020; Cavanagh et al. 1987).

Figure 4d displays the bottom section (heel), which is directly connected to the connecting structure in the middle. The actual shapes of the shoe components are illustrated as follows: the top section in Fig. 4e, the middle section in Fig. 4f, and the bottom section in Fig. 4g. Lastly, the fully assembled shoe is shown in Fig. 4h, which shows that straps are used to secure the shoes onto the user's feet and foam layers are added to ensure comfortable wear. The actuation mechanism that provides the inclination functionality is described.

We specifically target the inclination to the arch (middle foot area) because it is a low-pressure region. As observed by Cen et al. (2020), the midfoot did not experience a large increase in pressure during weight-bearing activities compared with the rearfoot and forefoot. Similarly, Cavanagh et al. (1987) reported that the midfoot carries only about 8% of the weight when the user is standing, confirming its low pressure relative to other foot regions. Therefore, the actuation mechanism exerts less power to achieve the desired inclination in this area than in other areas. Furthermore, because the human foot can be treated as a rigid body in the sole region (Zelik and Honert 2019) , adjusting the inclination at the midfoot affects the inclination of both the front and back parts of the foot.

4.2 ReD shoes control and interface

The actuation mechanism for the ReD Shoes is powered by an HSB-9381TH HITEC servo motor (HITEC 2025),

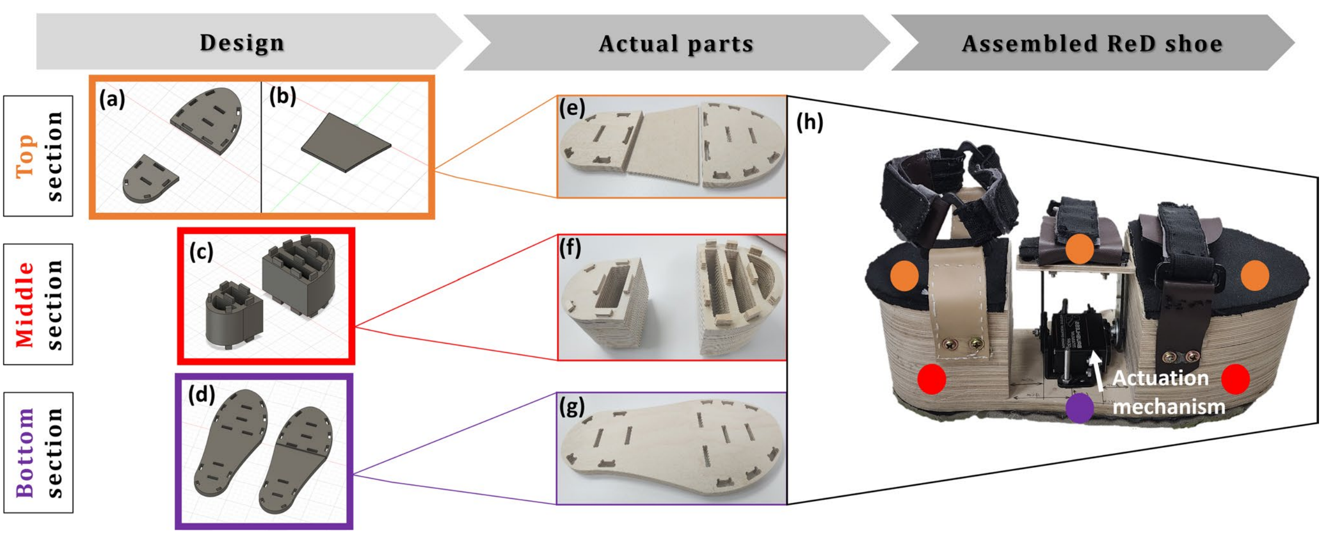


Fig. 4 Design and assembly of the ReD shoes: **a** stationary parts of the top section, **b** moving part of the top section, **c** middle section with front and back stationary parts, **d** bottom section, **e** actual shape of the parts of the top section, **f** actual shape of the parts of the middle section, **g** actual shape of the bottom section, and **h** fully assembled shoe with attached straps, foam layers, and actuation mechanism for functional inclination

which operates at a low voltage of 6 V and provides a maximum torque of 34 kg/cm. This servo motor facilitates 1-DOF movement, enabling the top section of the shoe to move right and left. A U-shaped metal bracket ensures that the distance from the motor shaft to the inclination surface is equal to 5.7 cm. This distance is calculated to guarantee that the delivered force is sufficient to manage the expected load, assuming that 8% of the participant's body weight (up to a maximum of 69 kg) is distributed over the mid-foot (Cavanagh et al. 1987). The maximum weight parameter was set as a controlled variable in our experimental setup. The control of the servo motor is managed by pulse width modulation using the LOLIN D1 mini microprocessor chip (LOLIN 2024), which supports WiFi communication through the ESP8266 module. Given the high current required by the servo motor, with a stall current draw of up to 2.7 A, the shoes and microprocessor are powered by two 2S LiPo batteries with sufficient power capacity. To ensure that the power isolation and distribution between the motors and the microprocessor are effective, we use a switch-mode buck regulator, the UBEC DUO (UBEC nd), with dual output channels. The operational commands are transmitted to the microprocessor via WiFi from the main processing personal computer (an ASUS ROG Zephyrus M16 laptop with a 12th Gen Intel Core i9-12900H processor with an NVIDIA GeForce RTX 3080 Ti graphics card), which runs the Unity 3D engine. These commands specify the travel direction and rotation angle, where the motor's home position sets the moving part of the top section to a fully horizontal orientation. The battery units, microprocessor, and switch-mode buck regulators were housed in a waist pouch, with power and control wires extending from the pouch to each ReD shoe, as illustrated in Fig. 5.

5 Main experiment: evaluating DT with varying inclinations using red shoes

This experiment was done to investigate how different inclination levels in ReD shoes affected the DT for RDW, using the DT measurement techniques of Steinicke et al. (2010). We also examined the effects of these inclinations on users' sense of presence, perceived workload, motion sickness, and overall comfort. Additionally, given that prior research has shown that VR and RDW systems cause instability (Hollman et al. 2007; Janeh et al. 2017), we analyzed gait stability to understand the impact of different inclinations on walking stability.

5.1 Experimental environment

The experiment was conducted in a 9×9 m lab room. During the experiment, we used an Oculus Quest 3 HMD and the right controller for participants to answer questionnaires administered during the study, as illustrated in Fig. 6. The experiment followed a within-participants design with three conditions: No Inclination, Low Inclination, and High Inclination. We employed Latin square randomization to determine the order of the conditions for each participant. The same equipment was used across all conditions to minimize bias. Seven RDW gain levels ($\pm\pi/90, \pm\pi/45, \pm\pi/30$, and 0) were randomly applied under each of the three experimental conditions, with six trials per condition, for a total of 42 walks per condition.

5.2 Conditions

Based on the pilot study results, we determined that the inclinations of 1.0 and 1.5 cm were the most effective at walking trajectory while minimizing discomfort. Therefore, we created three different conditions for the main experiment, and we used similar VR environments across all conditions.

- Condition 1 (No Inclination): In this condition no inclination was applied during the experiment.
- Condition 2 (Low Inclination): Under this condition, a 1 cm inclination was applied to the shoes. The inclination increased gradually as the curvature gain was applied, and it reached its maximum angle when the user reached the maximum curvature gain.
- Condition 3 (High Inclination): Under this condition, a 1.5 cm inclination was gradually applied, and it followed the same pattern as in Condition 2.

5.3 Participants

Twenty participants were recruited for the study, including 11 males and 9 females, aged between 18 and 31 years ($M = 21.4$, $SD = 2.91$). Their weights ranged from 48 to 69 kg. The participants came from diverse academic backgrounds, including biology, engineering, chemistry, and business administration, and they represented various nationalities and a broad spectrum of cultural backgrounds. This diversity was intended to make the findings more representative of and applicable to different populations, as has been suggested by previous research (Karjalainen 2020). Ten of the participants were familiar with the use of VR prior to the experiment. All participants were healthy, stable walkers with no neurological or brain conditions. Each participant received $20 in compensation for their 2 h of participation. The experiments conducted in this study were approved by

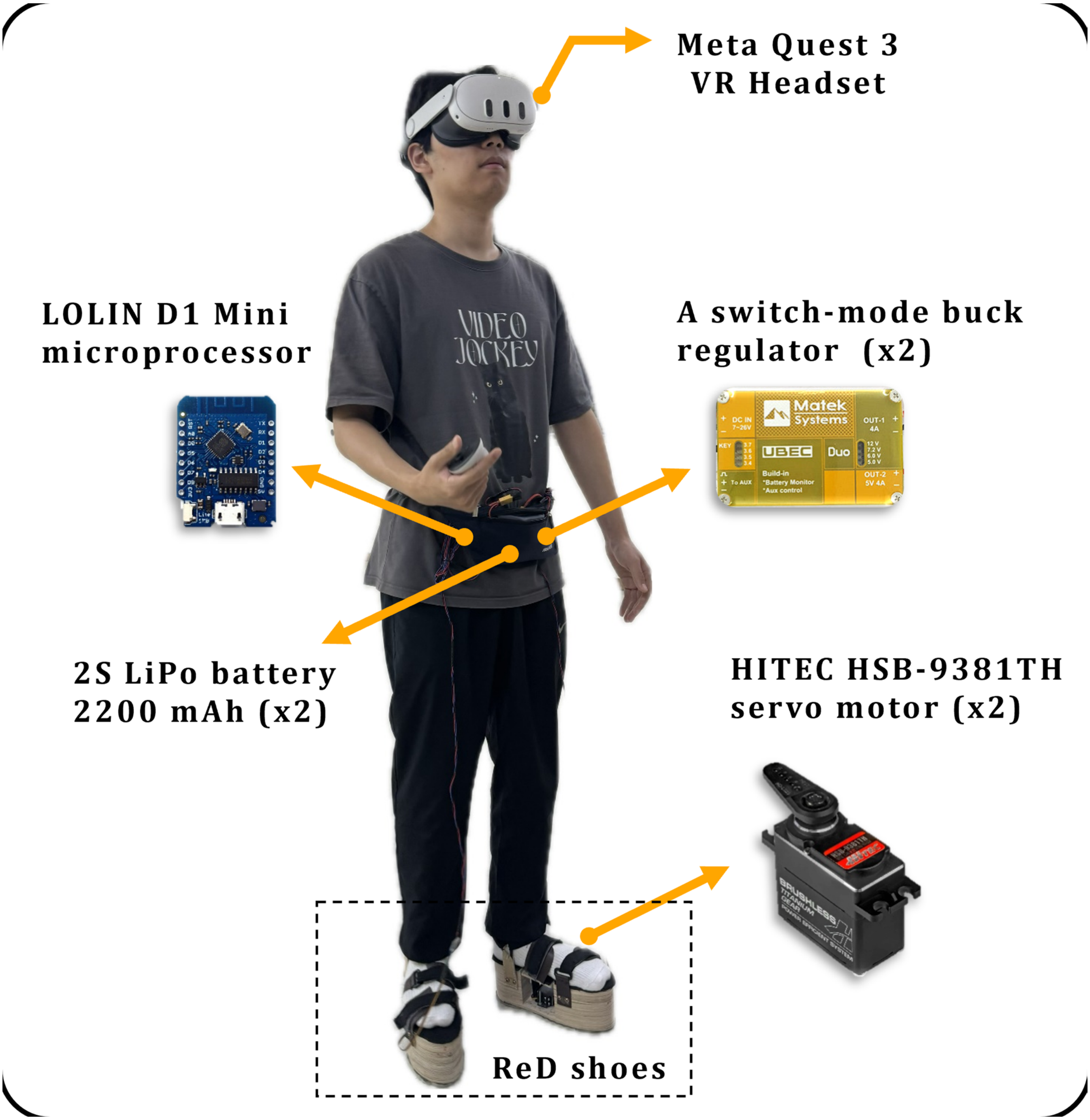


Fig. 5 Control and interface setup for ReD shoes, showing the placement of components and their connection to the user

the Institutional Review Board to ensure ethical compliance and participant safety.

5.4 Measurements

We collected physiological data along with responses from self-reported questionnaires and qualitative interviews for various measurements, including DT, gait stability, motion sickness, presence, perceived workload, and overall comfort and preferences.

To assess participants' ability to detect subtle manipulations of their walking path, the DT was measured using a 2AFC questionnaire based on the methodology of Steinicke et al. (2010). In every trial, the participants were asked. "Is the physical path bent to the left or the right?" and they responded by selecting either "left" or "right." To evaluate the degree of motion sickness induced by each condition,

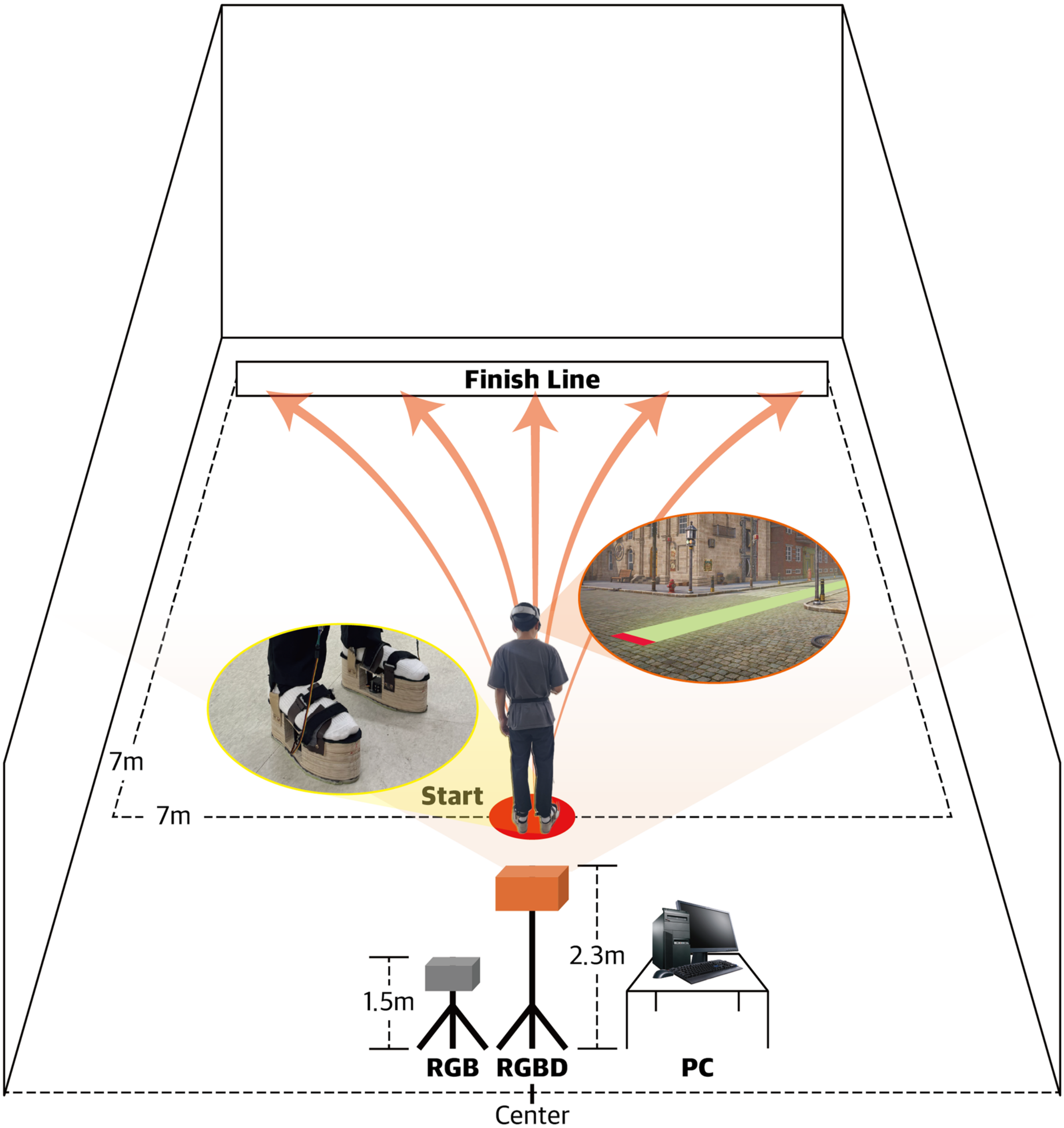


Fig. 6 Experimental setup showing a 7 m × 7 m test area with the main processing PC for handling computations, a depth camera for motion capture, and an RGB camera to record the entire experiment session

we employed the Simulator Sickness Questionnaire (SSQ), which uses a 4-point scale (ranging from none = 0 to severe = 3) to assess 16 symptoms categorized along three subscales: oculomotor, disorientation, and nausea (1993). Presence was assessed using the Igroup Presence Questionnaire (IPQ), which consists of 14 items that evaluate overall presence, spatial presence, engagement, and realism (Schubert et al. 2001). Perceived workload was measured using the NASA–Task Load Index (NASA–TLX), which includes six subscales—mental demand, physical demand, temporal demand, performance satisfaction, effort, and frustration—to compile an overall workload score (Hart and Staveland 1988). After they had completed trials under all the experimental conditions, the participants completed a final questionnaire on which they rated their overall preferred and most comfortable condition on a 5-point likert scale.

We evaluated gait stability by analyzing changes in the participants' CoM and by measuring several key metrics. To determine the CoM, we tracked the hip position markers in the MediaPipe's pose model (Lugaresi et al. 2019). We analyzed the total length of the three CoM trajectories in a single dimension: the anterior–posterior (C_AP), mediolateral (C_ML), and vertical (C_V) displacements. Along these trajectories, gait stability was characterized by smooth and consistent patterns of movement: minimal backward shifts in the C_AP trajectory, smaller lateral shifts in the C_ML trajectory, and minimal vertical oscillations in the C_V trajectory. The x, y, and z coordinates extracted using the MediaPipe pose model were adjusted to align with the user's walking plane: The x-axis corresponded to the C_V trajectory, the y-axis aligned with the C_AP trajectory, and the z-axis matched the C_ML trajectory. By integrating these metrics, we attempted to assess gait stability under different conditions when participants were using the ReD Shoes.

We also measured cadence, as defined as the number of steps per minute (Mohammadzada et al. 2022), as an additional indicator of gait stability. Higher cadence values typically suggest a more stable and consistent gait pattern that reflects the rhythm and regularity of walking cycles.

5.5 Procedures

Before they began the experiment, participants filled in informed consent forms and received comprehensive instructions outlining the experimental tasks. They also provided demographic and personal information, such as age, weight, and height, through a preliminary questionnaire. To ensure that they would be comfortable with the procedures, participants engaged in a practice trial before they began the main experimental sessions.

The participants were then fitted with ReD Shoes, which were adjusted to ensure that the straps were securely fastened and comfortably positioned around their feet. This meticulous fitting was essential to prevent any discomfort or slippage during the experiment, especially when the experimental inclinations were applied. Each participant wore the control system for ReD Shoes as a belt around their waist, and the electric wire connections from each shoe were routed along the participants' legs to ensure a secure and unobtrusive connection to the shoes and to minimize any potential discomfort or interference during the experiment. After they had been fitted with ReD Shoes, participants were asked to walk around for a short period to familiarize themselves with the shoes and adjust to the inclinations. Following this walk, the participants put on the VR headset and were instructed to stand at the designated starting point. The participants then began the trial session, it was confirmed that each participant experienced the ReD Shoes' inclinations in both directions.

After they had completed the trial session, the participants began the main experiment. They walked in a straight line for 7 m in the VE, with curvature gains applied after the first 2 m to prevent them from noticing the adjustments. This setup and walking distance followed the protocol established by Steinicke et al. (2010), as longer trajectories can introduce perceptual inconsistencies and increase the risk of motion sickness (Rebelo et al. 2025). After the curvature gain was applied, the shoe inclination gradually increased until it reached the required angle. After each 7 m walk, the participants answered the 2AFC questionnaire and then returned to the starting point for the next trial. This process was repeated 42 times (seven gains × six trials per gain) for each condition. We also introduced white noise in the background at the time the curvature gain was activated to block any sound from the motor, Fig. 6.

In the trial session, we observed that some participants, particularly in the High Inclination condition, often based their 2AFC responses on the direction of the shoe inclination rather than the actual walking trajectory, which led to confusion. This issue was similar to the problem reported in the results of the HR for RDW study (Fukui et al. 2023). To rectify this problem, we instructed participants to base their 2AFC responses on their actual walking trajectory. Additionally, we presented three of the six trials randomly in the main experiment to serve as confusion sessions. In these sessions, for example, a right inclination was applied to the shoes at the same time that the VE directed the walking trajectory to the left.

At the end of the experiment, participants were asked to remove the devices and complete a post-experiment survey for each condition, which included discomfort scores, the SSQ, the IPQ, an interview, and open-ended questions about their discomfort. Breaks were provided to the participants between experimental conditions to ensure participant comfort.

6 Results of the main experiment

6.1 Curvature DT analysis

The curvature measurements for each condition were examined using the 2AFC method. The results are presented in Fig. 7, which depicts the measured probability of the left responses of the participants for seven different curvature gains ($\pm\pi/90, \pm\pi/45, \pm\pi/30$, and 0). The standard error is

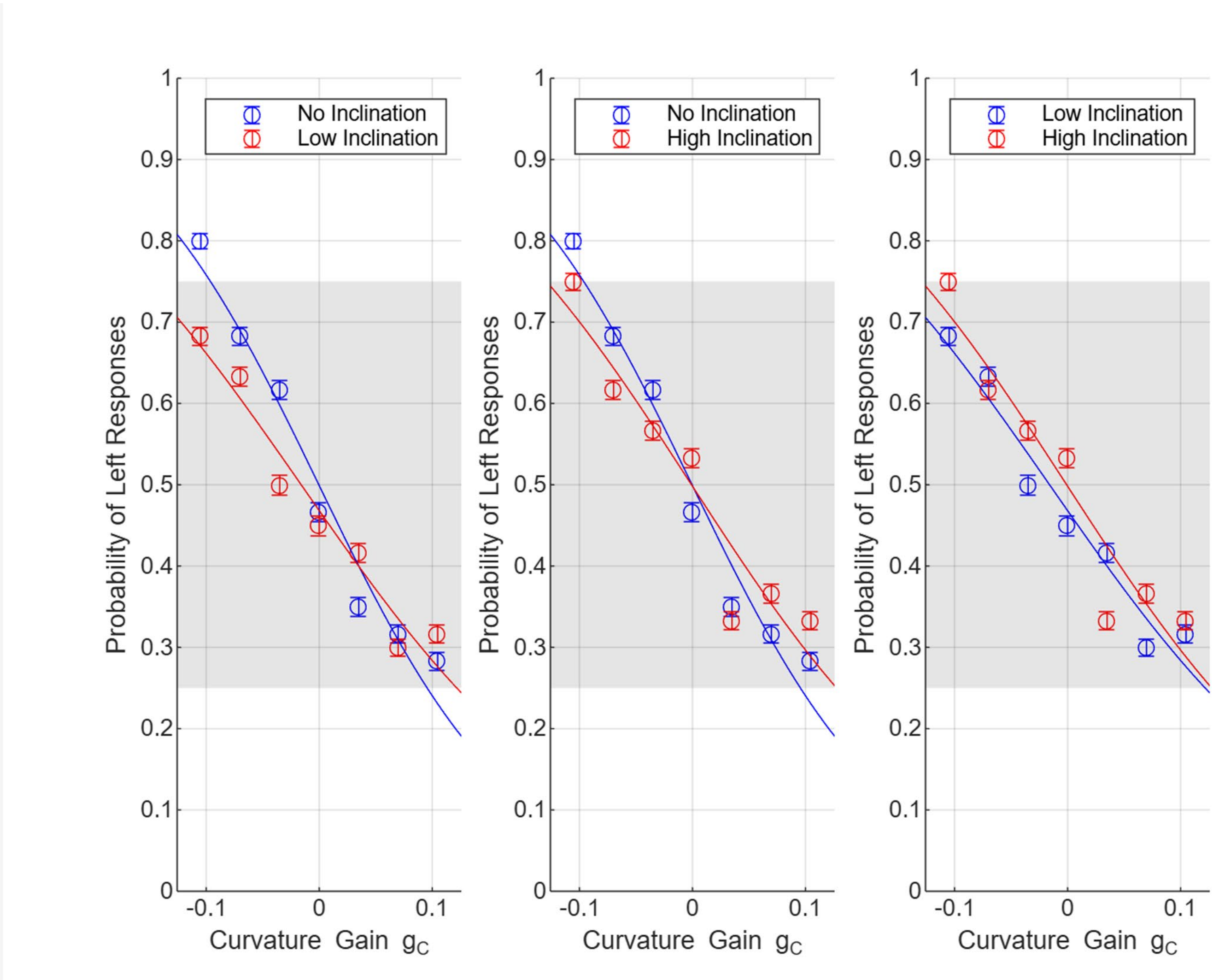


Fig. 7 DT expansion across conditions. The x-axis represents the curvature gain, whereas the y-axis represents the probability that participants perceive the path as curving leftward. Each data point is fitted to a psychometric function, where the shaded regions between the 25% and 75% probability lines are marked in gray. The figure compares the likelihood of left responses under the No Inclination, Low Inclination, and High Inclination conditions, thereby illustrating the effect of inclination on participants' perception of curvature

Table 2 Curvature DT results, including the Lower DT (LDT), Point of Subjective Equality (PSE), Upper DT (UDT), DT range, and the percentage difference compared with the No Inclination condition

Condition	UDT	PSE	LDT	DT_range	Difference (%)
No Inclination	0.0962	−0.0003	−0.0954	0.1916	–
Low Inclination	0.1536	−0.0160	−0.1216	0.2752	43.6359
High Inclination	0.1291	−0.0008	−0.1274	0.2565	33.8644

marked on each graph and the measured values were fitted using a sigmoid function.

The DT data presented in Table 2 show that the DT range increased under both the Low and High Inclination conditions compared with the No Inclination condition. Specifically, the Low Inclination condition showed the largest increase in DT range at 43.64%, while the High Inclination condition showed a 33.86% increase, Fig. 7. These findings suggest that inclination generally expands the DT range, reduces sensitivity to change in curvature and potentially improves obstacle avoidance in RDW. However, at higher inclinations (1.5 cm), the DT range expansion was narrower, which indicates greater sensitivity to curvature changes.

6.2 Simulator sickness

To assess the impact of each inclination condition on the symptoms of simulator sickness, participants completed the

SSQ after they completed the testing under each condition, Fig. 8. A repeated measures ANOVA showed no statistically significant differences between conditions; however, there was a trend toward a significant difference in overall SSQ scores between the three conditions, F (2, 38) = 3.172, p = 0.05. This suggests that although the differences were not measurable under conventional levels of significance, there is an indication that the inclination conditions might have affected the simulator sickness symptoms.

To further explore the specific impacts of each inclination condition, we analyzed the SSQ subscales—Oculomotor, Disorientation, and Nausea—separately, Fig. 9. The ANOVA test revealed a significant difference in the oculomotor subscale scores among conditions, F (2, 38) = 3.5919, p < 0.037. Participants reported significantly higher oculomotor symptoms under Condition 3 (High Inclination) (M = 6.966, SD = 5.279) compared with Condition 2 (Low Inclination) (M = 4.21, SD = 3.180, p < 0.04). For the disorientation subscale, no significant differences were found across the conditions, F (2, 38) = 0.3568, p = 0.7, which indicates that changes in inclination did not significantly impact the participants' disorientation symptoms. However, for the Nausea subscale, the ANOVA indicated a significant difference between conditions, F (2, 38) = 3.3810, p < 0.04. Despite this overall significance, post-hoc comparisons did not reveal specific pairwise significant differences between the conditions.

6.3 Immersion and presence

To understand how each inclination condition influenced the participants' sense of presence in the VR environment, we asked the participants to complete the IPQ questionnaire after they had experienced each condition. The repeated measures ANOVA test indicated significant differences in their overall sense of presence between the three conditions, F (2, 38) = 7.334, p < 0.002. Specifically, Condition 2 (Low Inclination) (M = 39.357, SD = 8.668) led to the highest sense of presence, which was significantly greater than in either Condition 1 (No Inclination) (M = 33.071, SD = 9.77, p < 0.03) or Condition 3 (High Inclination) (M = 30.5 SD = 8.285, p < 0.002), as shown in Fig. 10.

6.4 Perceived workload

Our results suggest that varying the inclination did not significantly affect the overall workload perceived by participants. The perceived workload scores were assessed by calculating the average scores for the six dimensions of the NASA–TLX questionnaire for the weighted data after each

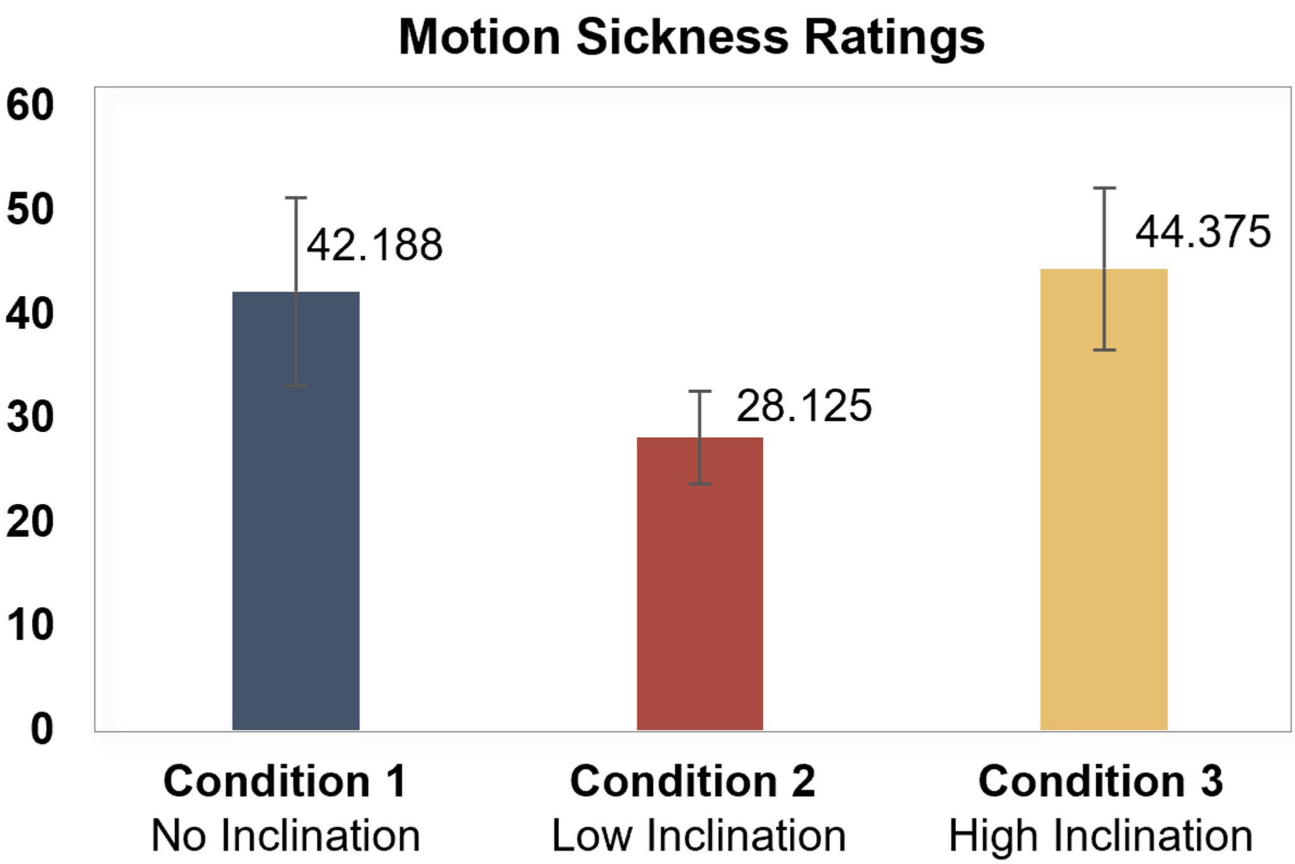


Fig. 8 DT Overall SSQ scores for the three conditions

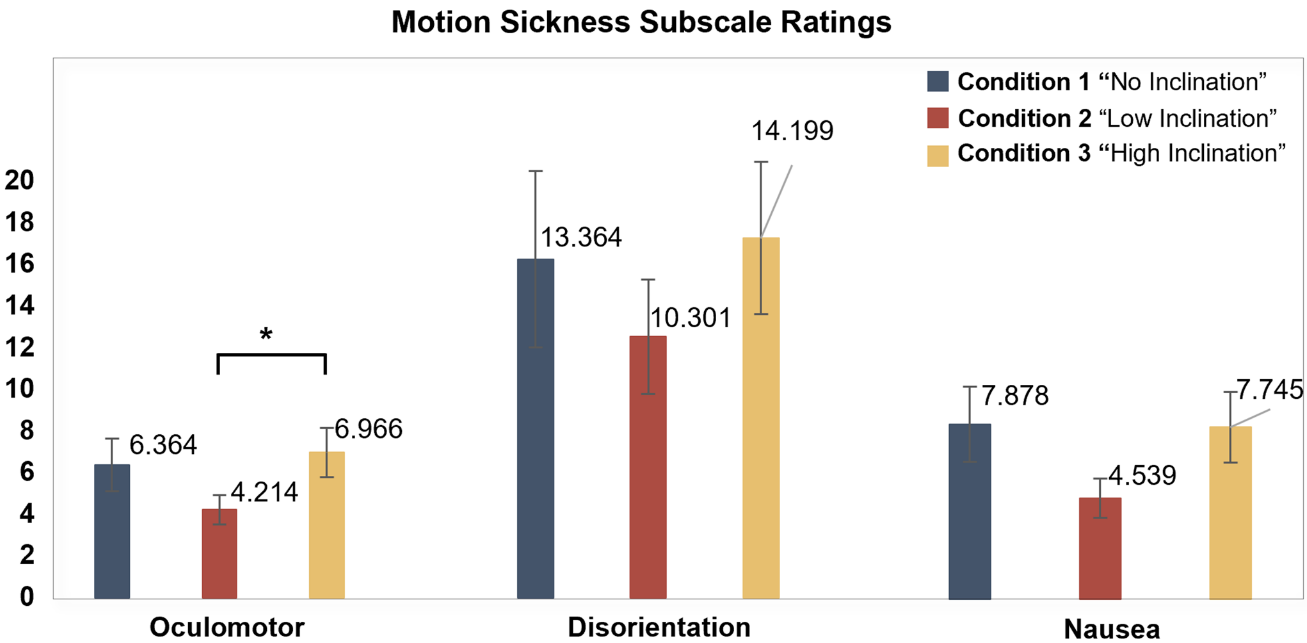


Fig. 9 Overall SSQ subscale ratings for the three conditions; the significance levels are *$p<0.05$, as indicated

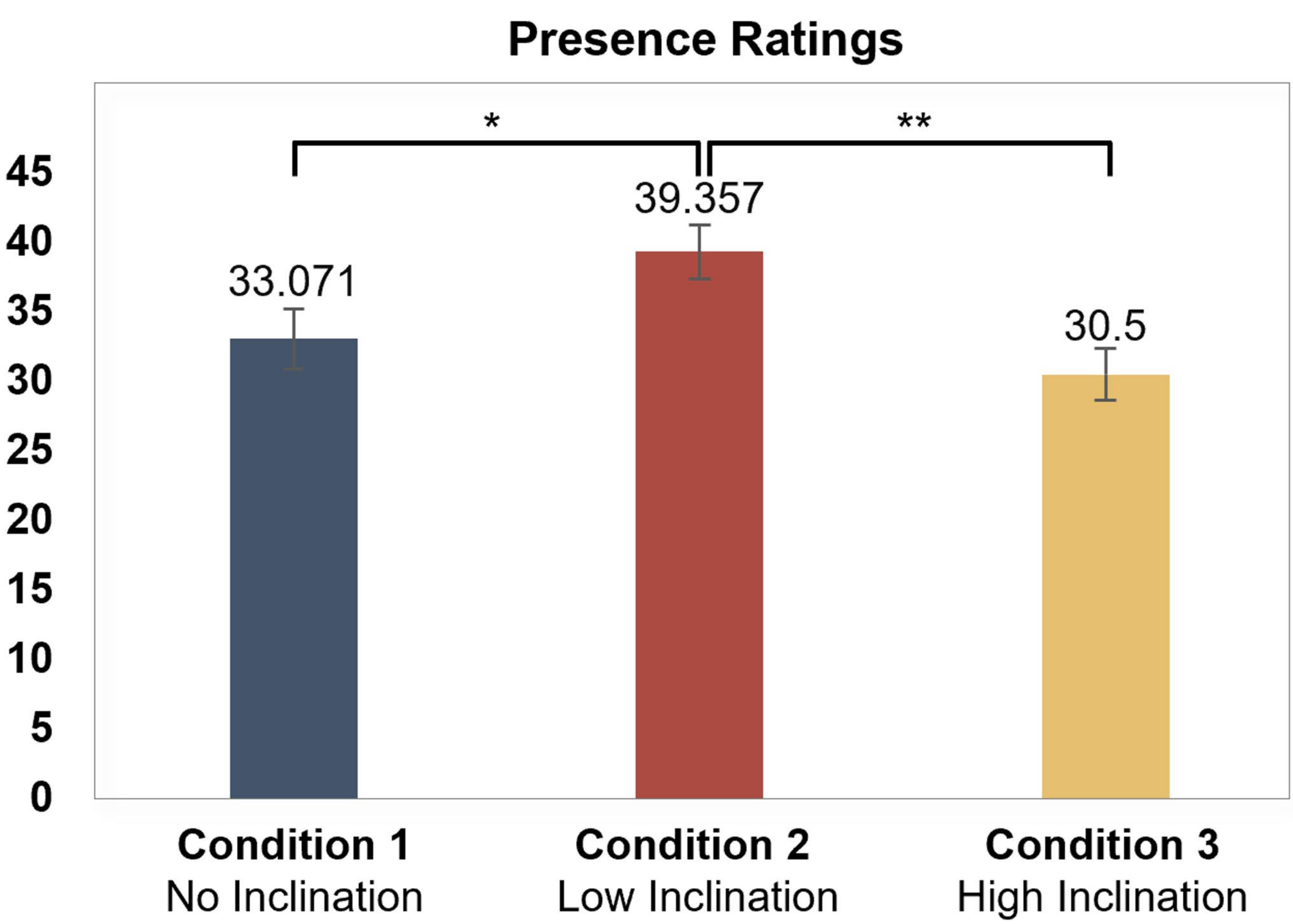


Fig. 10 Presence rating for the three conditions; significance levels are *$p<0.05$, and **$p<0.01$, as indicated

condition. The objective of this assessment was to understand how different inclinations applied to the user's foot affected the user's perceived workload. The ANOVA test results indicated that the differences in perceived workload between the three conditions were not statistically significant, F (2, 38) = 0.707, p = 0.5. However, when the mean values were compared, the perceived workload was slightly higher under Condition 3 (High Inclination) (M = 34.667, SD = 10.438) than it was under Condition 1 (No Inclination) (M = 32.667, SD = 11.962) or Condition 2 (Low Inclination) (M = 31.833, SD = 10.438), Fig. 11.

6.5 Gait stability analysis

We analyzed metrics derived from the center of mass (CoM) movements and step cadence to evaluate gait stability. The results revealed significant differences in gait stability, as measured by the CoM trajectory length and step cadence, between the three conditions. Since the normality assumptions were not satisfied for the CoM trajectory length and cadence, we employed nonparametric tests to assess these differences.

For the CoM X trajectory length, significant differences in gait stability were observed across the three conditions according to the Friedman test (χ^2 (2) = 12.510 and p = 0.002). A post-hoc analysis using Conover's test with Bonferroni correction revealed that Condition 3 (High Inclination) significantly reduced the participant's stability relative to Condition 1 (No Inclination) (p = 0.001). There was no significant difference between Condition 1 and Condition 2 (Low Inclination) (p = 0.179) or between Condition 2 and Condition 3 (p = 0.300). These results suggest that higher inclination levels adversely affect vertical stability, thereby increasing the risk of imbalance, as shown in Fig. 12.

For the 3D CoM XYZ trajectory length, significant differences in gait stability were observed between the three conditions based on the Friedman test (χ^2 (2) = 7.974, p = 0.019). A post-hoc analysis using Conover's test with Bonferroni correction revealed a significant difference between Condition 1 (No Inclination) and Condition 3 (High Inclination) (p = 0.025), whereas no significant differences were found between Condition 1 and Condition 2 (Low Inclination) (p = 1.000) or between Condition 2 and Condition 3 (p = 0.091). These findings suggest that the higher inclination levels significantly impacted gait stability, specifically

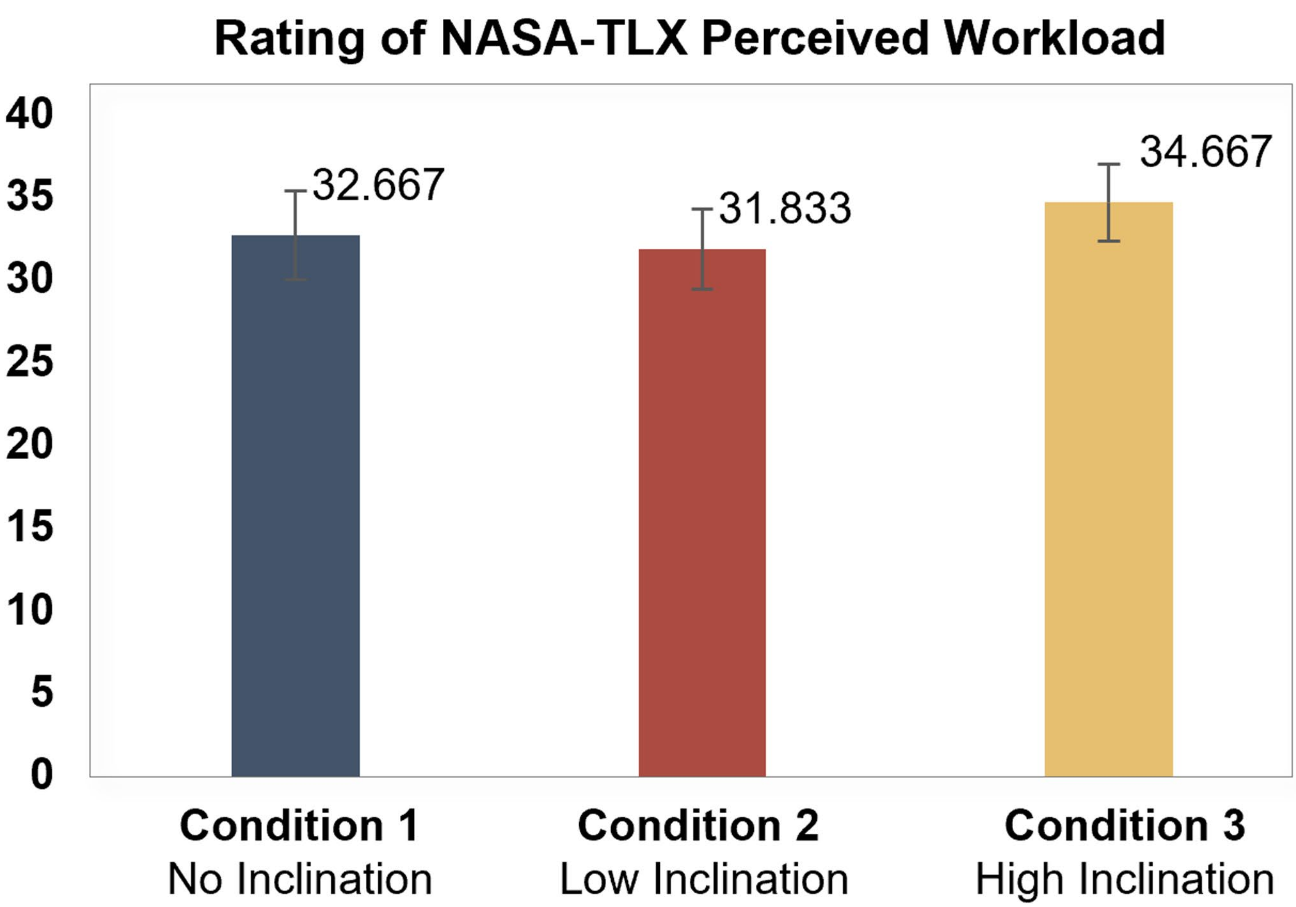


Fig. 11 Perceived workload (NASA–TLX) for the three conditions

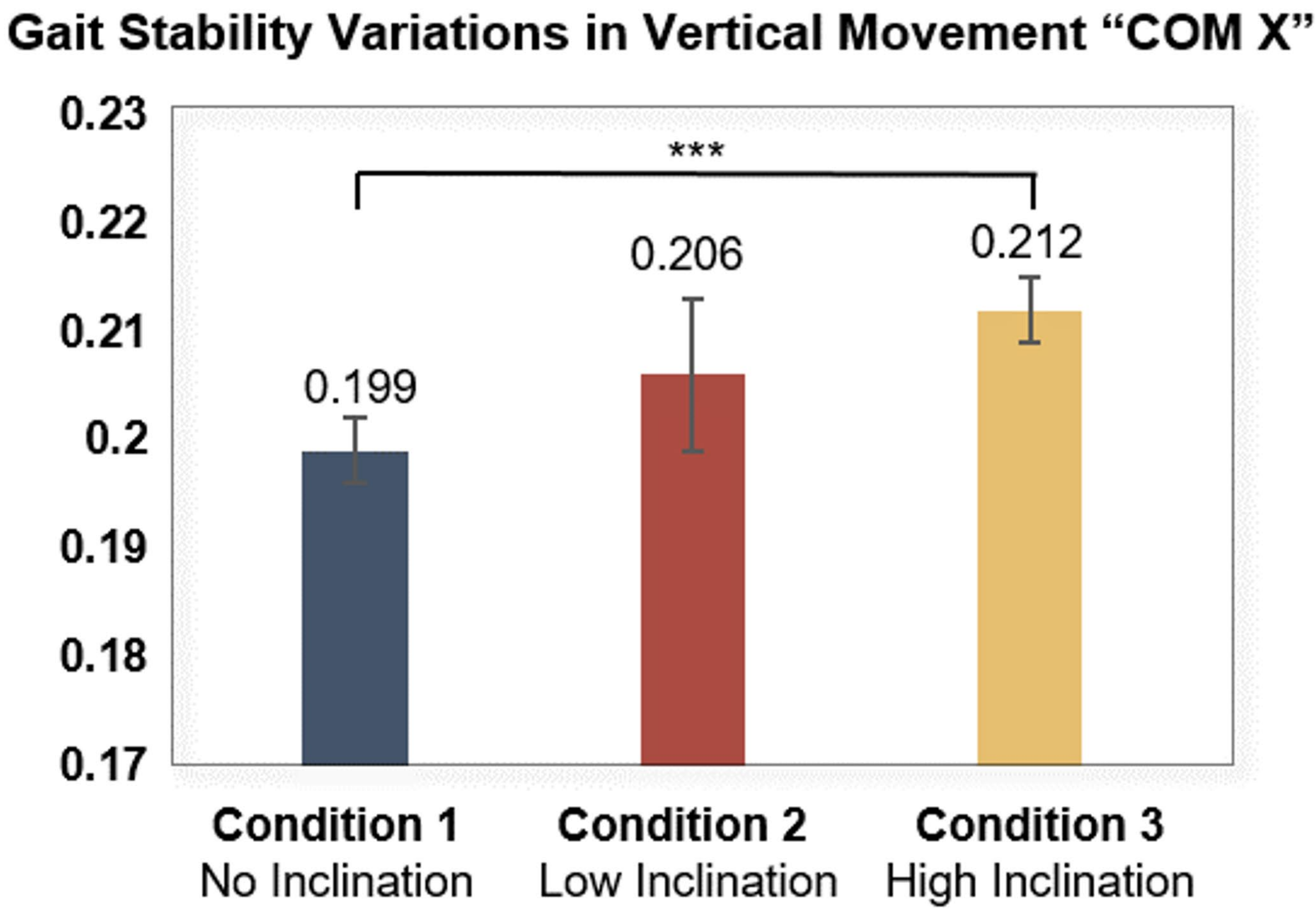


Fig. 12 Center of Mass (CoM) X trajectory length for gait stability across each condition. The error bars indicate standard deviation. ***$p<0.001$

in comparison with the No Inclination condition, and that differences between low and high inclination levels were not statistically significant, as shown in Fig. 13.

Cadence, which was measured as steps per minute, showed significant differences in gait stability across the conditions, as determined by the Friedman test (χ^2 (2) = 23.303, $p<0.001$). A post-hoc analysis using Conover's test with Bonferroni correction revealed that Condition 1 (No Inclination) did not significantly differ from Condition 2 (Low Inclination) ($p=0.335$, Bonferroni-corrected $p=1.000$). However, Condition 1 had a significantly higher cadence than did Condition 3 (High Inclination) ($p<0.001$, Bonferroni-corrected $p<0.001$). Similarly, Condition 2 also had a significantly higher cadence than did Condition 3 ($p<0.001$, Bonferroni-corrected $p<0.001$). These results suggest that increased foot inclination significantly reduces cadence and may indicate greater instability or a more cautious walking pattern under challenging conditions, as shown in Fig. 14.

These findings suggest that higher inclinations applied to the foot can negatively impact gait stability and particularly affect metrics such as the CoM trajectory length and cadence, both of which are crucial to maintaining balance during walking. The significant reduction in cadence and increased CoM trajectory length observed for the higher inclination conditions highlight potential challenges in maintaining stability under such circumstances. Although not all metrics revealed significant differences across all conditions, the results of the Friedman test and Conover's post-hoc test with Bonferroni correction indicate that the high inclination levels in particular pose a greater risk to gait stability than do the No Inclination conditions.

6.6 Preference and comfort

The participants rated their overall preferences and comfort on a scale from 1 (very low) to 5 (very high) after they had completed the testing for all three conditions. The results indicated that participants preferred the Low Inclination condition (Condition 2) and also found it to be the most comfortable option for experiencing VR Fig. 15.

The ANOVA test revealed significant differences in the overall preference rates between the three conditions, F (2, 38) = 5.807, $p<0.006$. The post-hoc comparisons showed that participants significantly preferred Condition 2 (Low

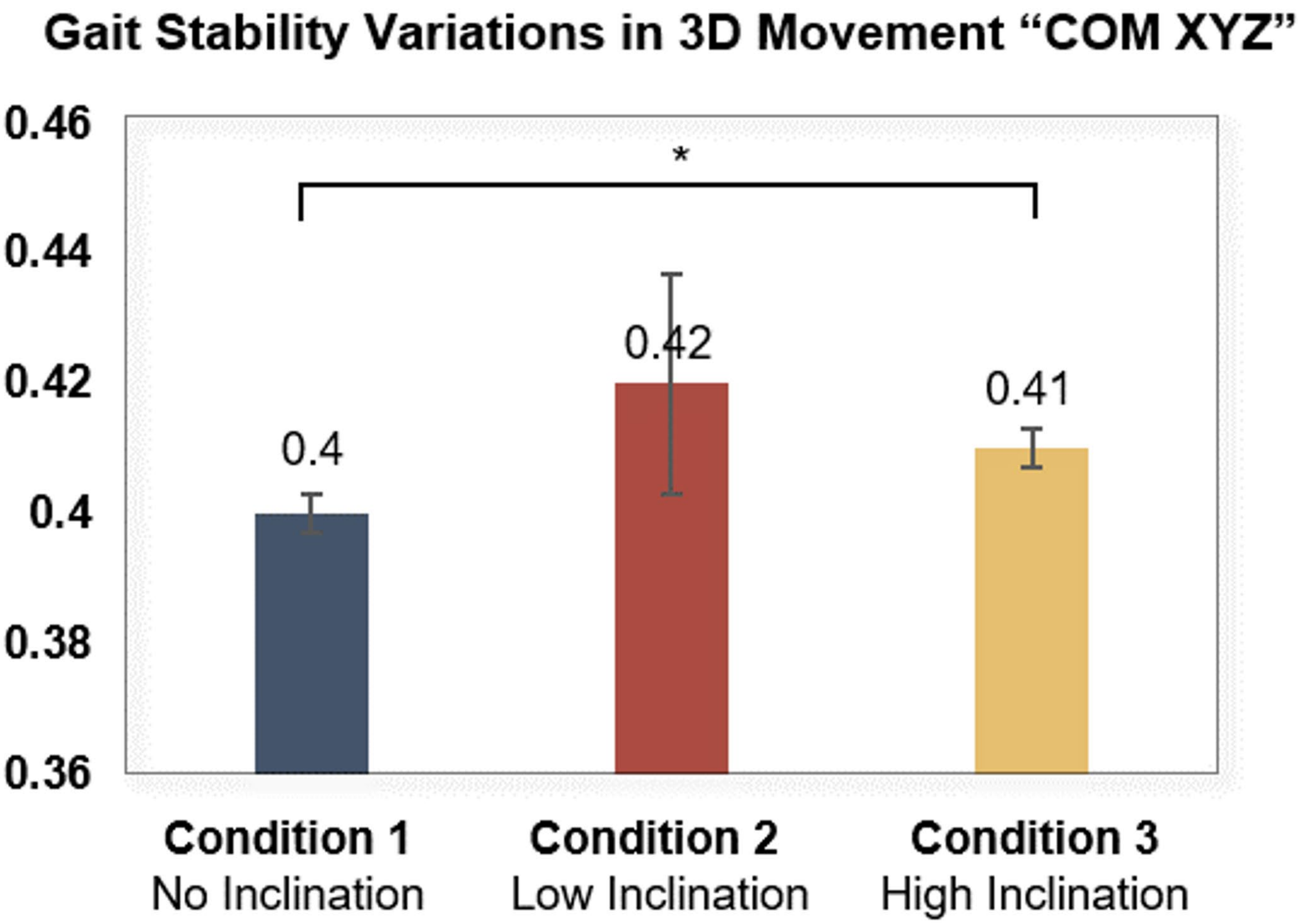


Fig. 13 CoM XYZ trajectory length for gait stability across each condition. The error bars indicate standard deviation. $*p<0.05$

Inclination) ($M=4.1$, $SD=0.968$) over Condition 1 (No Inclination) ($M=2.45$, $SD=1.538$, $p<0.008$) or Condition 3 (High Inclination) ($M=2.75$, $SD=1.552$, $p<0.02$). These results suggest that moderate inclination levels enhance user comfort and preference, whereas both No Inclination and High Inclination were less favored.

7 Discussion

In this study, we explored how the alignment of vestibular, visual, and haptic cues, modulated through different levels of inclination applied via ReD Shoes, influences walking behavior in RDW, DT, gait stability, sense of presence, perceived workload, and user comfort in VE. The findings provide preliminary insights into how inclination settings can minimize user discomfort while enhancing engagement and stability during VR experiences. In the following sections, we analyze each of the research questions in light of our findings, discussing their implications for refining the design and functionality of ReD Shoes. Furthermore, this study highlights how inclination integration can improve DT interpretation and expand the potential of ReD Shoes in enhancing RDW in practical VR applications.

7.1 Impact of inclinations level on DT for RDW (RQ1)

Our results indicated that the inclinations applied through ReD Shoes expanded the DT for RDW compared with the No Inclination condition. The Low Inclination condition (1 cm) showed the largest expansion in DT range (43.64%), suggesting that slight inclinations reduce users' ability to detect deviations in their walking paths, thereby enhancing the RDW experience. In contrast, the High Inclination condition (1.5 cm) resulted in a smaller DT expansion (33.86%), indicating that greater inclinations may increase users' sensitivity to curvature changes, Table 2. Although haptic feedback can enhance the VR experience, the amount of feedback is important; too much feedback may cause discomfort and VR sickness (Ohashi et al. 2023), which makes the manipulations more noticeable (Hwang et al. 2023a, b). In our case, under the High Inclination condition the ReD Shoes may result in a lower DT expansion due to the impact of intense feedback. Figures 12, 13, and 14 illustrate that the

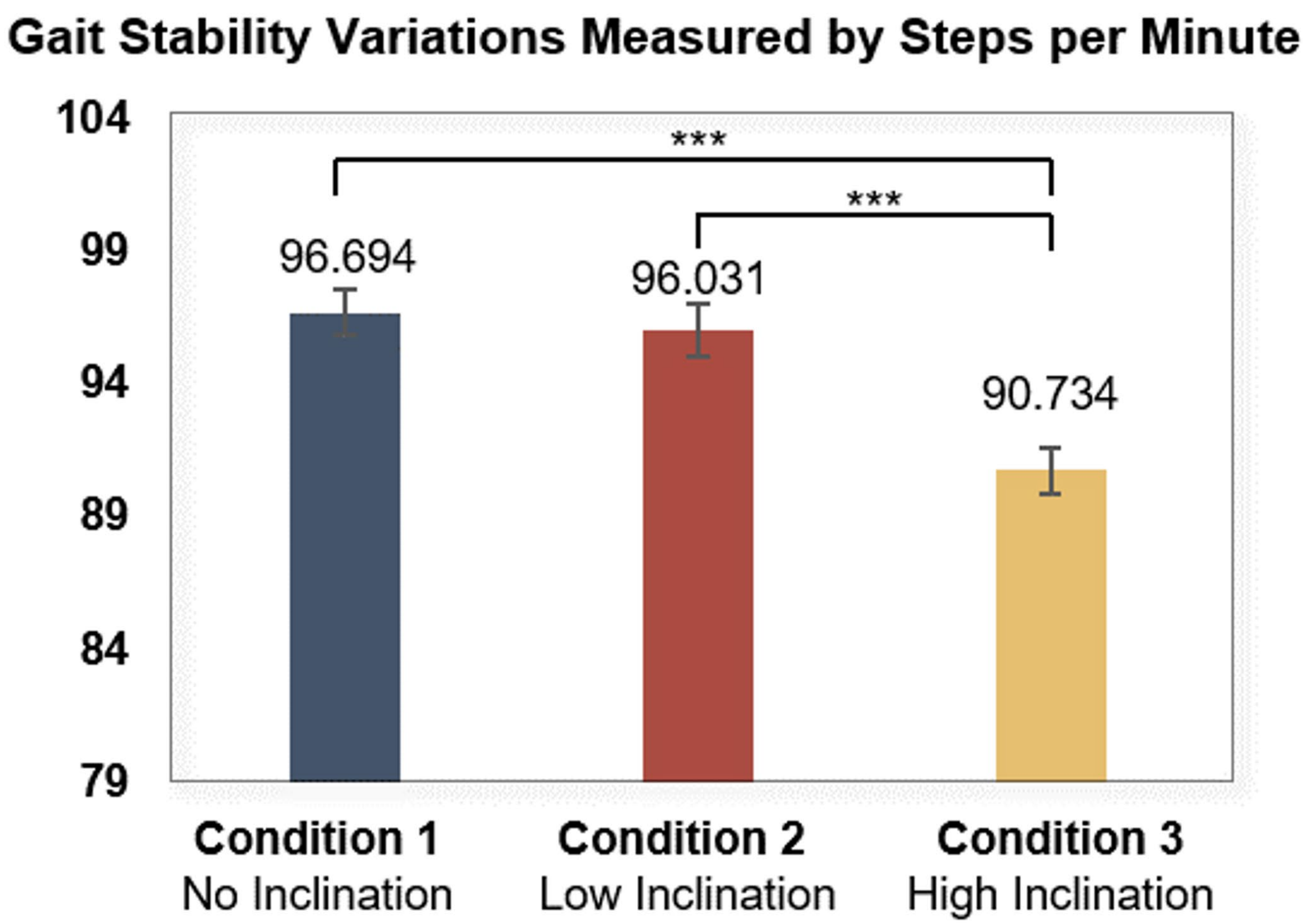


Fig. 14 Steps per minute for gait stability across different inclination conditions. Error bars indicate standard deviation. ***$p < 0.001$

High Inclination condition may lead to a significantly more unstable gait than do the No Inclination and Low Inclination conditions. This decrease in gait stability due to more salient haptic cues increases users' sensitivity to variations in movement, thereby limiting the effectiveness of RDW. These results align with previous studies that indicated that reduced gait stability in VEs heightens sensitivity to changes in walking paths, ultimately diminishing the expansion of the DT (Steinicke et al. 2010). Participant feedback further supports these findings: as most participants reported feeling as though they were repeatedly moving in a straight line in the Low Inclination condition. This suggests that even subtle tactile cues can affect the perception of movement direction, underlining the importance of fine-tuning the inclination levels to optimize the RDW experience.

7.2 Influence of different level of shoes inclination on motion sickness, presence, and workload (RQ2)

7.2.1 Motion sickness and sensory integration

The analysis of motion sickness across different levels of shoe inclination reveals how variations in tactile feedback intensity influence user comfort during VR experiences. Although no notable differences were observed in the overall motion sickness scores across conditions, there was a trend toward more symptoms under the High Inclination condition, Fig. 8. This finding suggests that although moderate inclination (as seen in the Low Inclination condition) does not remarkably contribute to motion sickness, extreme inclination may increase discomfort or lead to symptoms under certain conditions.

Breaking down the SSQ subscales into oculomotor, disorientation, and nausea symptoms further highlights the specific effects of inclination on motion sickness, Fig. 9. The High Inclination condition was associated with significantly higher oculomotor symptoms compared to the Low Inclination condition. This indicates that the intensity of the

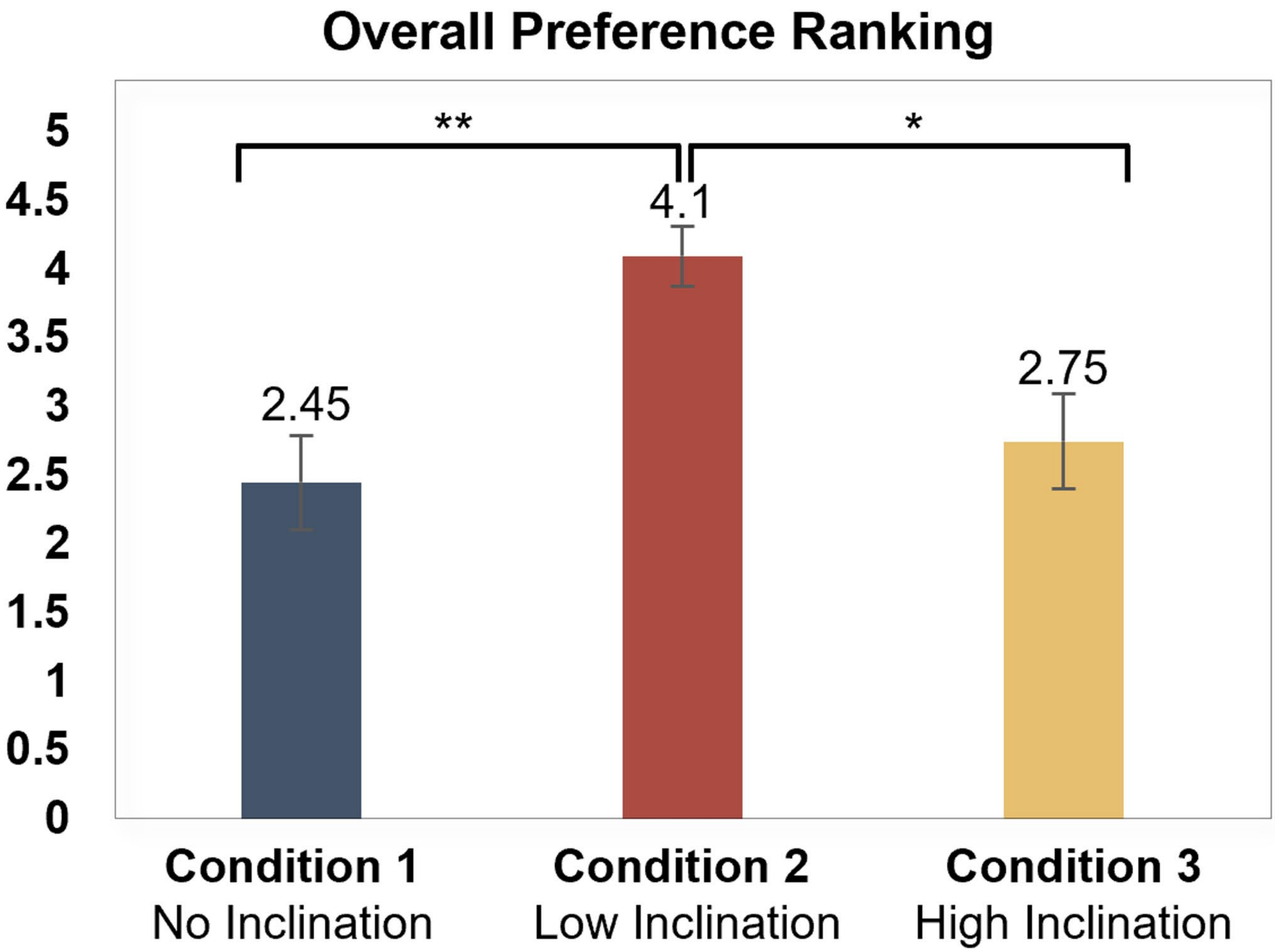


Fig. 15 Overall preferences for the three conditions

haptic feedback in the High Inclination condition increases the strain on the visual and vestibular systems, as they must work harder to process and reconcile conflicting sensory inputs. For instance, greater inclinations require users to exert more effort to maintain balance, which may heighten sensitivity to visual–vestibular mismatches, resulting in eye strain and related discomfort. This observation is in line with previous research that indicated that a more extreme inclination could disrupt the sensory integration necessary for comfort in VR (Luo et al. 2023).

Interestingly, the disorientation subscale showed no notable differences between conditions, suggesting that variations in inclination do not substantially influence spatial orientation and that moderate inclination is unlikely to cause notable disorientation. However, the overall considerable differences between conditions and the observed trend toward increased nausea under the High Inclination condition, even without distinct pairwise differences, indicate the potential for higher inclinations to contribute to mild nausea symptoms. These findings highlight the need to optimize the inclination level for minimizing discomfort and reducing the risk of motion sickness.

7.2.2 Sense of presence and gait stability

The results demonstrate that the haptic sensations provided by different shoe inclinations significantly affected the user's sense of presence in the VR environment (Fig. 10). The Low Inclination condition led to the highest sense of presence, markedly greater than that observed in either the No Inclination or High Inclination condition. This improvement can be attributed to the enhanced multisensory integration facilitated by the Low Inclination condition, where tactile feedback to the feet closely aligns with visual stimuli. In contrast, the High Inclination condition reduced the users' sense of presence, likely due to the increased effort required to maintain balance and stability. The need to compensate for instability may have diverted participants' attention from the VR experience, thereby diminishing their sense of presence. Similarly, the absence of tactile feedback under the No Inclination condition limited the alignment between the visual and haptic cues, resulting in a reduced sense of presence.

These findings are supported by the gait stability results, which showed that the High Inclination condition was the least stable of all conditions. This instability not only contributed to discomfort but also required participants to focus more on the tactile sensation applied to their feet, which further detracted from their engagement with the virtual environment. These results highlight the importance of selecting optimal inclination levels to maintain gait stability, enhance multisensory integration, and maximize the user's sense of presence in VR environments.

7.2.3 Perceived workload and adaptation

Interestingly, the perceived workload did not differ significantly across conditions (Fig. 11). This suggests that the participants were able to adapt to the various inclinations without experiencing excessive cognitive or physical strain. Initially, the users may have encountered some discomfort due to the unfamiliarity of the ReD shoes. However, as they got used to the shoes during the trial sessions, they maintained a steady level of workload.

7.3 Effect of inclinations on walking behavior and gait stability (RQ3)

Gait stability analyses revealed that different inclinations had a significant impact on participants' walking behavior. The 1D CoM X Length (Fig. 12) showed significant differences in gait stability between the High Inclination and No Inclination conditions ($p<0.001$), which suggests that higher inclinations can significantly destabilize the user gait, particularly affecting vertical balance. Moreover, although no overall notable differences were detected in the 3D CoM XYZ length (Fig. 13), the notable difference between the No Inclination and High Inclination conditions ($p<0.025$) suggests that even if the general stability is maintained, certain dimensions of the movement can be adversely affected by the High Inclination. The decrease in cadence observed in the High Inclination condition further supports the notion that high inclinations disrupt normal walking patterns and walking comfort (Horsak et al. 2023), as shown in Fig. 14. Participants likely adopted a more cautious gait to compensate for balance challenges, which may have increased physical strain and the potential risk of falls.

These findings imply that higher inclinations may disrupt natural gait and increase the risk of imbalance, which is critical in the design of VR systems to ensure user's safety. Conversely, the Low Inclination condition resulted in better gait stability. This observation supports the Low Inclination condition use in RDW applications in which maintaining a natural gait is crucial.

7.4 Overall preference and comfort

The findings on user preferences and comfort further support the benefits of the Low Inclination condition. Participants notably preferred the Low Inclination condition over the No Inclination and High Inclination conditions. These results indicate that the Low Inclination condition not only enhances user comfort but is also favored by users when engaging in VR. The preference for the Low Inclination condition indicates that it strikes the right balance between providing effective tactile feedback and minimizing discomfort, which aligns with the overall goal of optimizing the RDW experience.

Participants reported that they found it somewhat boring and felt lost without the applied haptic feedback as in the Low Inclination condition. In contrast, the high inclinations were described as distracting, which may have contributed to user discomfort. These qualitative insights underscore the importance of balancing inclination levels to enhance both the functional and preference aspects.

8 Conclusion, limitations, and future directions

This study introduces the first instance of actuated VR footwear, the ReD Shoes, specifically designed for RDW applications. We investigated the impact of varying shoe inclinations on key aspects of the RDW experience, including DT expansion, gait stability, sense of presence, motion sickness, perceived workload, and user comfort. Our findings suggest that a low inclination of 1 cm offers an optimal balance for enhancing RDW performance. This condition expanded the DT range (43.64%) while maintaining gait stability, enhancing the sense of presence, and minimizing discomfort and motion sickness. In comparison, the high inclination condition (1.5 cm) resulted in a smaller DT expansion (33.86%) and was associated with increased gait instability, discomfort, and oculomotor symptoms, which heightened users' sensitivity to walking path deviations. These results underscore the impact of inclination levels in actuated VR footwear on RDW by affecting DT expansion, gait stability, user comfort, and motion sickness mitigation.

Although our study explores the effects of inclined shoes on RDW in VR, the ReD Shoes were produced in a fixed size, which may not have fitted all participants perfectly. Future designs should offer adjustable sizing mechanisms—such as modular insoles or extendable frames—to accommodate diverse foot shapes and sizes. Research has demonstrated that personalized insoles significantly reduce pressure–time integrals at critical regions like the forefoot and heel—areas typically overloaded in individuals with high arches—thereby enhancing comfort and reducing gait variability (Ma et al. 2024). This personalization not only enhances tactile fidelity and comfort but also enables the system to adapt effectively to users with different gait characteristics.

Further, the current ReD Shoes apply uniform haptic cues regardless of individual gait patterns. However, gait parameters such as cadence, stride length, and phase timing vary significantly across users, impacting how tactile feedback is perceived and utilized. Future improvements could incorporate a brief calibration phase to capture the gait dynamics and adjust feedback parameters of each user accordingly. Integrating this adaptive approach into ReD Shoes would likely enhance haptic intuitiveness, user comfort, and biomechanical effectiveness across diverse gait profiles (Demircan 2020). Additionally, our study focused solely on curvature gain as the redirection method, given its close alignment with natural locomotion and continuous path adjustment. However, rotation and translation gains are also essential in RDW and can significantly affect user experience. Future research should investigate how shoe inclination interacts with these gains to provide a more holistic understanding of physical cue integration in RDW systems.

Furthermore, the relatively small sample sizes (n = 10 in the pilot and n = 20 in the main experiment) and limited age range (mean age in the early 20 s) of this study constrain the generalizability of the findings. While these parameters align with prior exploratory RDW studies (e.g., Steinicke et al., 2010; Fukui et al. 2023), future research should include larger and more age-diverse participant cohorts to improve statistical power and assess age-dependent variability. Although previous studies have shown no significant differences in VR experience measures such as presence, usability, or motion sickness across younger and older adults (e.g., Dilanchian et al. 2021; Zelik and Honert 2018), age is known to affect gait variability and locomotor adaptation, particularly under sensory perturbations. Broadening the age spectrum will able a comprehensive understanding of how VR haptic feedback systems such as ReD Shoes interact with user-specific physical and perceptual profiles.

Additionally, even though the High Inclination condition was not generally preferred by participants for RDW, some found it to be interesting and enjoyable. This suggests that while high inclinations may not be suitable for standard RDW applications, they can be effective in other VR scenarios. For example, gaming and more dynamic environments may benefit from heightened sensations that increase user engagement and enjoyment. The current study focused specifically on RDW techniques; therefore, future studies should explore these alternative applications to better understand the versatility of the ReD shoes in different virtual contexts. By addressing these limitations, future research will be able to refine the design and application of the ReD shoes to improve comfort, stability, and overall effectiveness in various VEs.

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Author contributions Aya Ataya (A.A.) and Ahmed Elsharkawy (A.E.) contributed equally to this work. Jieun Lee (J.L.), Seokhyun Hwang (S.H.), Minwoo Seong (M.S.), and SeungJun Kim (S.K.) also contributed to the study. A.A. was responsible for conceptualization, methodology, software development, hardware design, validation, formal analysis, writing the original draft, and visualization. A.E. contributed to conceptualization, software development, hardware design, validation, writing the original draft, and visualization. J.L. contributed to conceptualization, methodology, hardware design, formal analysis, and writing—review & editing. S.H. contributed to software development and providing resources. M.S. was responsible for data curation and visualization. S.K. supervised the project and contributed to writing—review & editing.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval The research was approved by the Institutional Review Board (IRB No. 20240807-HR-77-04-04).

Informed consent We informed and obtained consent from each participant prior to research engagement.

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